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All communications should be addressed to the Editor.

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Notices of the Royal Aëronautical Society.

The Chairman.

At the meeting of Council, held on July 5th, Major-General R. M. Ruck, C.B., C.M.G., R.E., was re-elected Chairman of the Society.

The Council.

Sir Mackenzie D. Chalmers, K.C.B., has been elected to the vacancy in the Council caused by the death of Mr. B. G. Cooper.

Appointments.

Lieutenant-Colonel Bagnall Wild, C.M.G., R.E., Fellow, has been appointed Brigadier-General.

New Members.

The following new members have been elected in the various grades:—

Fellow.—Mr. H. C. Watt.

Associate Fellows.—Mr. T. D. Carpenter, Major H. W. Prance, Mr. P. C. Thornton, Mr. J. H. Wolfe Flanagan, Mr. H. Glaser, Mr. J. Kenworthy.

Member.—Mr. H. N. Skerrett.

Associate Members.—Mr. Bata Kirshna Sinha, Mr. W. H. Sadgrove, Mr. R. C. Moore, Mr. S. Benstein.

Committees.

The following Committees of the Council have been appointed:—

Lectures Committee.—Lieut.-Col. M. O'Gorman, C.B.; Capt. A. P. Thurston, D.Sc.; Brig.-Gen. R. K. Bagnall Wild, R.E.; Capt. A. Graham Clark, R.A.F.; Mr. M. A. S. Riach; Mr. F. W. Bramwell; Capt. F. M. Green, R.A.F.

Finance Committee.—Capt. A. P. Thurston; Major A. R. Low, R.A.F.; Mr. G. Holt Thomas; Mr. H. White Smith.

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Technical Terms Committee.—Lieut.-Col. O'Gorman; Mr. W. Cannell (S.B.A.C.); Mr. Seabrook (S.B.A.C.); Mr. R. K. Pierson (S.B.A.C.); Capt. Day (Admiralty and War Office); Col. Landon (Air Ministry); Capt. Myers (Air Ministry); Mr. Selby (National Advisory Committee); Sir Napier Shaw (Meteorological Office); Mr. L. Bairstow (Technical Dept.); Col. Cave (Airships); Major Ewen (Stores Dept.); Major Low; Mr. A. S. A. Ormsby (Patent Office); Lieut. McKinnon Woods (Royal Aircraft Establishment); Mr. W. G. Renals (Liaison Officer, American Advisory Committee); Major Clarson (Engines); Mr. C. G. Grey (Royal Aero Club); Mr. R. B. Matthews; Mr. Stevens (Royal Aircraft Establishment); Major Stewart (Instruments); Capt. Mountain (Stores).

Representative on Engineering Standards Committee.—Lieut.-Col. O'Gorman.

Representatives on Steel Research Committee.—Mr. F. Handley Page; Lieut.-Col. O'Gorman.

THE WIND CHANNEL: ITS DESIGN AND USE.

SUMMARY.

Discussion of the value of model experiments.
Description of wind channels other than those at the N.P.L.
Description of two first and subsequent channels at the N.P.L., with an account of the airscrew balance. Chief precautions to be observed in erecting the main balance and the methods by which its accuracy is checked.
Measurement of wind velocity.
Comparison between the channels, with some figures of the cost of the newer ones.
Discussion on some of the methods of supporting models.
Stability of aircraft. Short account of the investigations which have been carried out, with an explanation of the system of axes used. Description of the methods of carrying out the various wind channel tests.
Remarks on the corrections to be applied for change of scale and speed.
Conclusion.

BY J. R. PANNELL, A.M.I.M.E., FELLOW.

It has long been realised that experiments in the laboratory on small models afford in certain cases a means of obtaining, cheaply and rapidly, information on the behaviour of the actual structure under the conditions in which it is to be used. This plan has been adopted in many branches of science, and in none to a larger extent than in naval and aeronautical architecture. The problems to be investigated are usually those connected with the motion of bodies through a fluid, but if we accept the principle of relative motion we have an alternative method open to us for our model experiments. We may, if we wish, reverse the conditions and set the fluid in motion, the model remaining stationary. Generally speaking, one plan has been adopted in naval architecture and the other in aeronautics. In the former case models are towed through water in a ship tank, while in the latter they are placed in a tube through which air is passed. One difficulty in the case of the moving fluid is to estimate the velocity, and, mainly for this reason, a certain amount of experimental work has been carried out in air by moving the body on a whirling arm. This plan was invaluable in providing a standard anemometer calibration, but this done, there is only an extremely small amount of work which cannot be carried out more satisfactorily in the wind channel. The stationary model offers many advantages, particularly in connection with measurements of the forces acting upon it, and the writer is of the opinion that the method might be applied with advantage in experiments on ship models to a greater extent than has hitherto been the case.

The application of model results to the actual structure is often a matter of considerable difficulty, but as the amount of information obtained in aeronautics increases, it appears probable that the change of the coefficients in passing from model to full scale (which is small in the majority of cases) will soon be known with considerable accuracy. Under these circumstances the value of model experiments becomes very high, and it appears that the performance of an aeroplane can be predicted by this means with considerable accuracy.

It must be clearly understood, however, that the value of model experiments is entirely dependent on their accuracy. Changes in parts of an aeroplane may often cause appreciable differences in the performance, though the parts themselves may be so small as to be difficult of reproduction at all on a 1/12th scale model. An instance of this may be cited. It has been stated that in a certain

type of aeroplane the substitution of streamline for circular wires caused an increase of 10 miles per hour in the speed, yet it is quite certain that only the highest experimental accuracy would enable the difference to be measured on a 1/12th scale model.

Again, some experiments were carried out on a 1/25th scale model of a large biplane in order to determine, among other things, the angle at which the tail plane of the machine should be set and the position of the rudder hinge, in order that the rudder should be just stable. The model experiments determined the required angle of the tail plane, and showed that the model rudder would be neutral if the hinge were moved forward a few thousandths of an inch. The determination of the latter quantity represented the extreme limit of accuracy, but it was found in the actual machine that the rudder was rendered stable by a forward movement of the hinge of an inch or so. Moreover, this machine was one of the earliest of its size, and it was feared that an error in the setting of the tail plane (which was based on the results of the model experiment) might give rise to forces on the machine greater than those which could be exerted by the controls. The machine, however, carried out its trials without accident, and the type is to-day one of the most successful of British bombers. If it be conceded that the model experiments prevented accident to only *one* machine, the saving in mere money was sufficient to carry on the work of the entire Aeronautical Department of the National Physical Laboratory for many months.

When the author was invited by the Secretary of the Society to prepare a paper on "The Wind Channel" he was at once impressed by the fact that such a general title could only be justified if a description of all the channels in which satisfactory experiments had been carried out, was included. An attempt has therefore been made to describe briefly the more important channels of the world, as far as they are known to the writer, the greatest attention being paid to those in which results of obvious value have been obtained. The author's actual experience is, however, limited to the channels at the National Physical Laboratory, and the paper must be regarded as mainly a description of that type. It is difficult to avoid bias in favour of apparatus with which one is familiar, but the writer believes that this type of low resistance channel, in which the air is drawn from a large reservoir, is unequalled for accuracy and rapidity of operation. This view was supported by Lieutenant J. C. Hunsaker, of the United States Navy, who, after a tour of the principal aerodynamical laboratories of the world, recommended the erection at the Massachusetts Institute of Technology at Boston, U.S.A.,* of a four-foot channel which in all the essential details is an exact copy of those at the N.P.L.

It may be remarked that considerable progress has been made since the apparatus and methods described in this paper were in use, but the exigencies of the present situation forbid the publication of any further details.

It will be convenient to group the channels under the countries to which they belong, and we may commence with the one which perhaps did more than any other, in the early days of aviation, towards the development of practical types of airships and aeroplanes.

FRANCE.

A small wind channel was erected at the military establishment at Chalais-Meudon, which was in charge of Colonel Renard, as long ago as 1877, and constitutes the earliest channel known to the writer. It was 13ft. long and had a diameter of 2½ft. A considerable amount of work appears to have been carried out on models of airships, but the results were regarded as confidential and were not published.

*Described in the Smithsonian Misc. Col., Vol. 62

A very extensive laboratory was founded in 1911 by M. Deutsch de la Meurthe at St. Cyr. It includes laboratories, workshops, administration building, several wind channels, and an open-air track upon which runs an electrically-driven carriage. Experiments are made on this carriage with full-size aeroplane wings, and it is by this work that the St. Cyr Laboratory is most generally known.

No printed details of the channels are available, but the form is understood to be that of a Venturi tube of circular section with the balance situated underneath the channel. The current is produced by a Sirocco fan of large diameter.

A very large amount of experimental work has been carried out in the laboratory of Eiffel, situated in the Champ de Mars, Paris. The laboratory was constructed about 1910, and contained a circular channel nearly 5ft. in diameter, in which experiments were made in continuation of those with falling plates on the Eiffel Tower. The general arrangement of the channel is shown in Fig. 1. The characteristic feature of the channel is that the experiments are made in an hermetically sealed room (Fig. 2), in which the pressure is equal to the static pressure in the channel. The air stream crosses this room without any solid boundary, and it is stated that larger models can be used than is the case if the stream is confined within rigid boundaries, no sensible eddies being set up. The length of the chamber is 12ft., and a conical receiver projects slightly into it on the outlet side. A balance is provided for measurement of lift, drag, and moment, the observers sitting on a platform above the free stream.

A 65-h.p. motor was used, and a speed of 65ft./sec. attained. Several anemometers of the pressure head type were employed, and compared with the drop of pressure in the closed chamber. The velocity calculated from this pressure difference by the formula

$$V^2 = 2gh$$

was 1½% higher than that given by the pitot tube.

A new laboratory was opened in 1912 at Auteuil. The channel is constructed on exactly the same principle as the earlier one, but the diameter has been increased to 6½ft. The air is led into the test chamber by a reducing cone whose diameter changes from 13ft. to 6½ft. in a length of 11ft. The stream leaves the test chamber by a bell-mouthed opening and passes to the "discharger," which is a cone increasing from a diameter of 6½ft. to 11ft. (which is the diameter of the fan) in a length of 30ft. This design is stated to be very efficient, as the air reaches the fan at a low velocity and at a pressure little above that of the hall into which it is delivered. A 50-h.p. motor is provided, and a maximum speed of 100ft./sec. is attained.

Experiments have been carried out in these channels covering a very wide range of subjects, including the determination of forces and moments on aerofoils, complete models, and bodies, pressure plotting experiments, and tests on series of airscrews.

The convenience of an arrangement which enables the observers to be placed in the sealed test chamber is no doubt great, but it is open to question whether the accuracy of results obtained in this free current is so high as those obtained by the more generally accepted methods.

It has been shown that an error of 0.2° in the assumed wind direction would cause an error of 6% in the value of the drag of an aeroplane model.

ITALY.

The principal aerodynamic laboratory in Italy is that of the Brigata Specialisti. It is situated near Rome, and is under the charge of Major Crocco. The apparatus included a wind channel in which very elaborate precautions were taken to secure uniformity of the flow. The air was forced by the fan into a

closed chamber, where the velocity was reduced and the pulsations partly damped out. It then passed to another chamber larger than the first, from which it entered the experimental channel, which was 2.5ft. square. Several layers of gauze were introduced, and the flow was stated to be satisfactorily uniform to within a short distance of the wall. The model was supported on the balance

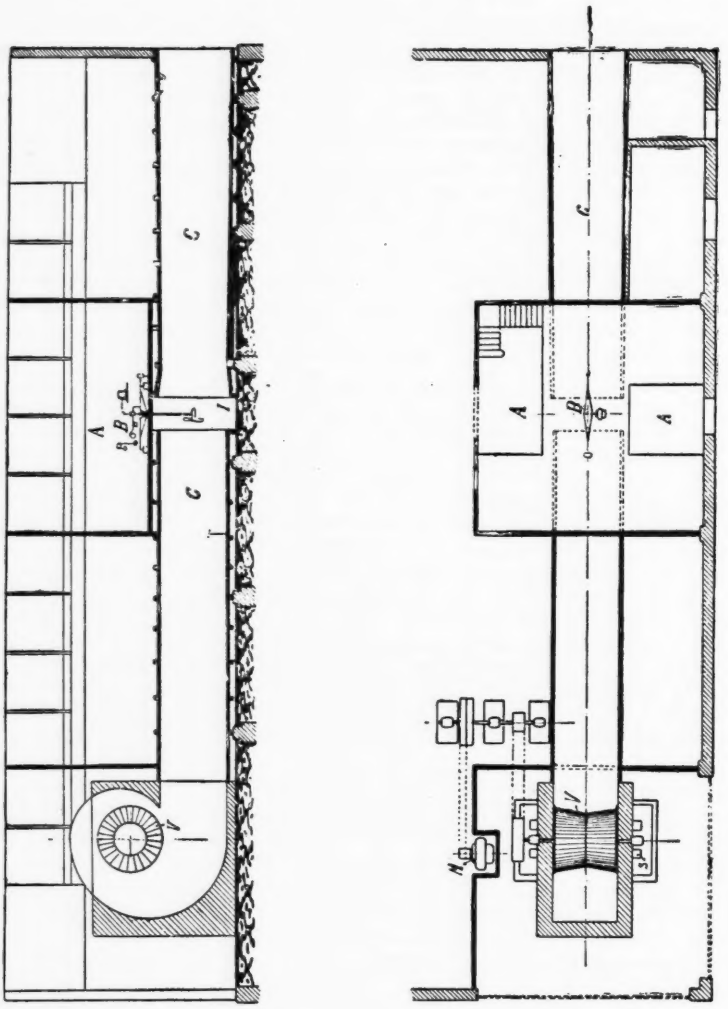


FIG. 3.
An Italian Channel of 1912.

just outside the end of this channel, so that at the section of the stream at which the experiments were made there was no solid boundary.

Several balances were in use, that provided for the most accurate measurements being supported on the surface of a vessel of water; the principal part of the wind force was balanced by weights attached to a cord passing over a pulley. Records of the movement of the balance were obtained by means of

additional apparatus, in which electric sparks were passed through specially-prepared paper.

In 1912 the laboratory was reorganised under the title Lo Stabilimento di esperienze e costruzione Aeronautiche del Genio, and a new wind channel of an entirely different type was erected. This channel, shown diagrammatically in Fig. 3, is 6½ft. square and 22ft. long, the air current being produced by a Sirocco (centrifugal) fan, belt-driven from a 30-h.p. electro motor. The balance is placed in a sealed test chamber, there being a gap of about 3¼ft. at the position at which the experiments are made. The method of test is thus similar to that of Eiffel, except that the length of the " free " stream in which the measurements are made is much less. The test-room is divided into two parts, the upper of which contains the balance and its observer, while in the lower is placed the manometer and various other instruments. The speed of the air current can be regulated from this chamber by opening or closing shutters on the intake side of the fan.

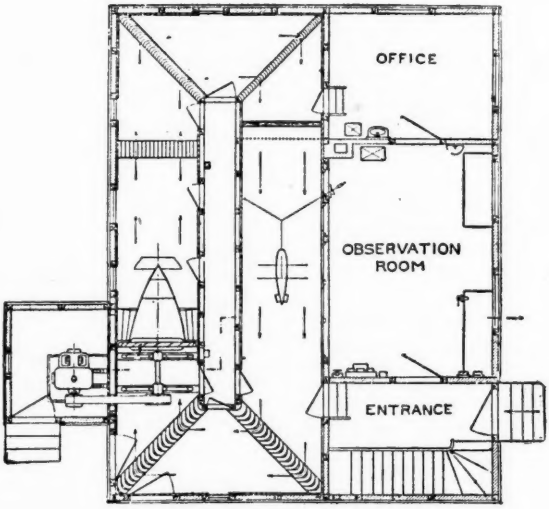


FIG. 4.

Plan of Prof. Prandtl's Laboratory at Gottingen.

Two anemometers are used, one situated upstream of the test section and another placed near the outlet of the channel. The uniformity of the flow is improved by the introduction, near the fan, of a layer of gauze and a honeycomb, and it is stated that over a period of one or two minutes (the time required for an observation) the flow can be kept sufficiently steady. The range of velocity available is from about 7ft./sec. to 52ft./sec. Experimental work of considerable value had been carried out in this laboratory till the year 1914, but information as to the results obtained since that date is not at present available.

GERMANY.

The principal Aerodynamic Laboratory in Germany was that at Göttingen, of which Prandtl was in charge. The general arrangement of the laboratory is shown in Fig. 4. This channel is of the enclosed type, in which the air circulates continuously round an approximately rectangular path. The test section of the channel is 6½ft. square, but if high speeds are required an

octagonal liner can be fitted, reducing the diameter to about 3.3ft. Guide blades are provided at the corners and a honeycomb and gauze screens are introduced to secure uniformity in the flow. To this end also the walls of the honeycomb are made double, so that any cell can be partly closed by bending one of the walls across it. The gauze is also rendered finer where necessary by painting. The arrangements for the measurement of forces are unique, separate balances being provided for lift and drag, a total of four being required for the complete investigation of forces and moments. The model is suspended on wires and is restrained in a horizontal plane by two wires at an angle of 120° to each other. One of these wires is fastened to the wall of the channel, while the other passes through it and is attached to the drag balance. The drag is calculated from the increase in tension of this wire when the air current is started.

Four supporting wires are brought to a light rod, placed along the wind direction, from which the model is suspended, but it appears to the writer preferable to attach the wires to the model directly, as in the case of a low resistance form the flow has been found to be very sensitive to small obstructions. This modification may perhaps have been subsequently introduced. Each pair of wires is taken to a balance above the channel for measurement of lift, and the fourth balance is used in obtaining rolling moments

The velocity is measured by a kind of pitot tube with an inclined tube alcohol manometer, and an automatic regulator is provided to maintain a constant speed. This regulator consists of two bell jars, hung, with their lower ends under water, from a balanced arm. One jar is connected to the channel immediately in front of, and the other immediately behind, the airscrew, a pressure difference proportional to the square of the wind speed being thus obtained. The speed is set to the desired value by the regulating resistances and a weight on the regulator balance set to a position marked upon it for the required speed. A change of speed now causes the balance arm to move over to one stop operating a resistance in the field circuit of the motor. The stops are also mounted on a swinging arm whose motion is damped by a vane moving in a fluid. This latter device reduced " hunting " due to over-regulation.

A —-h.p. electro motor drives the fan, a maximum speed of 33ft./sec. being attained in the 6½ft. channel and 55ft./sec. when the section is reduced to 3¼ft.

For several years before the war the work carried out in this channel dealt mainly with the resistance of streamline bodies, including measurements of pressure distribution. Experiments have also been made on the resistance of spheres, and to a limited extent on aeroplane models, though the latter branch of study has doubtless been extended recently.

AMERICA.

A wind channel was erected in an Aerodynamical Laboratory at Washington in 1901 by Mattulath. The section was 6ft. square and the length 40ft. The current was produced by a fan 5ft. in diameter driven by a 12-h.p. electro motor, a maximum speed of 40ft./sec. being attained. It was provided with a balance for measurement of lift and drag, and with a torsion balance.

This channel was used by Zahm in 1904 for his experiments on the skin friction of flat boards. The method adopted was to suspend the boards by wires from the roof of the laboratory and observe their displacement under the wind forces.

No complete description of this channel has been available, but it appears to be of a satisfactory type. As far as the writer is aware, however, no important work has been carried out since that of Zahm.

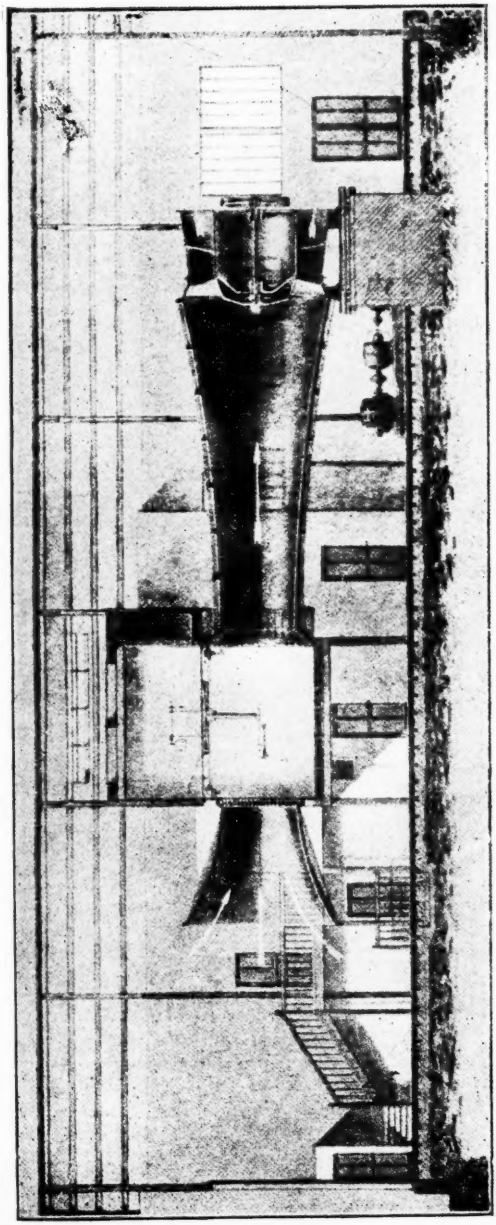


FIG. 1.

M. Eiffel's Channel: General Arrangement.

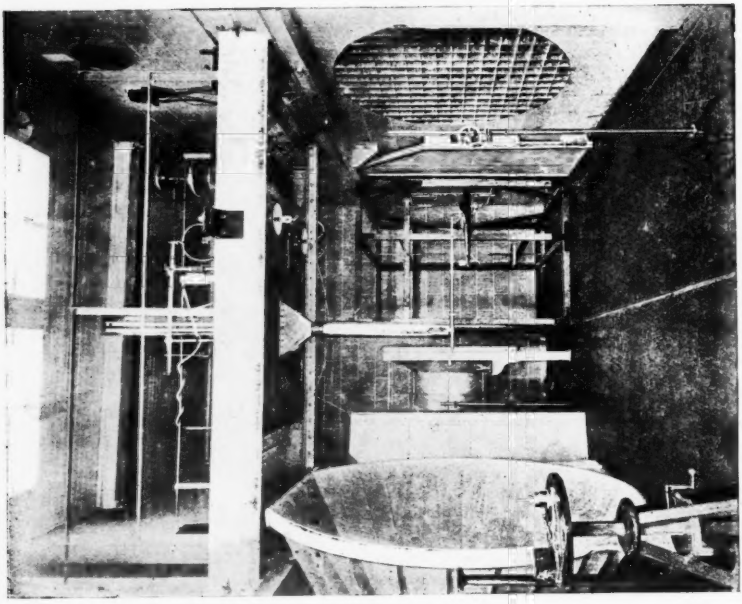


FIG. 2.
M. Eiffel's Channel: The Test Chamber.

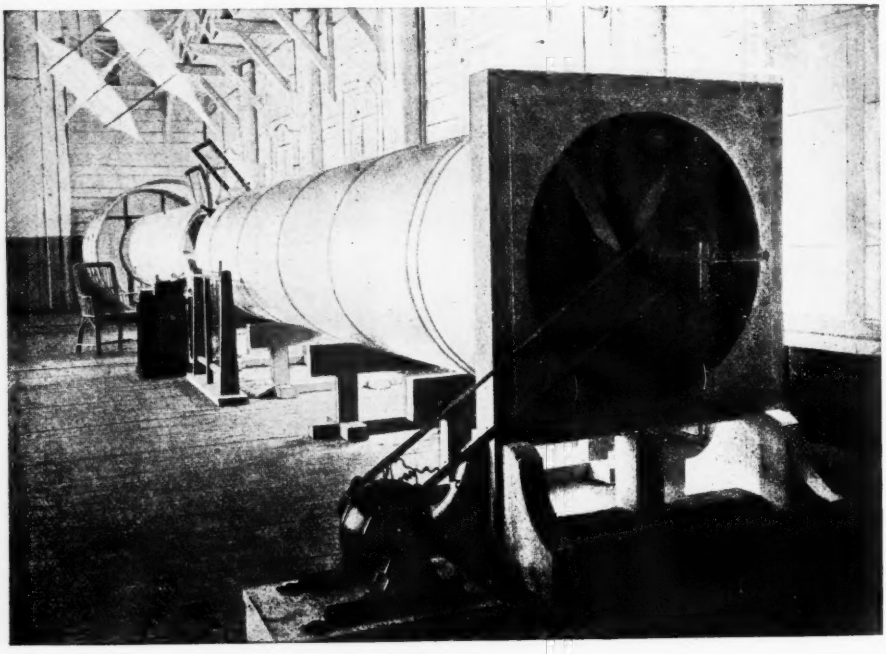


FIG. 6.
The Russian Channel at Koutchino.

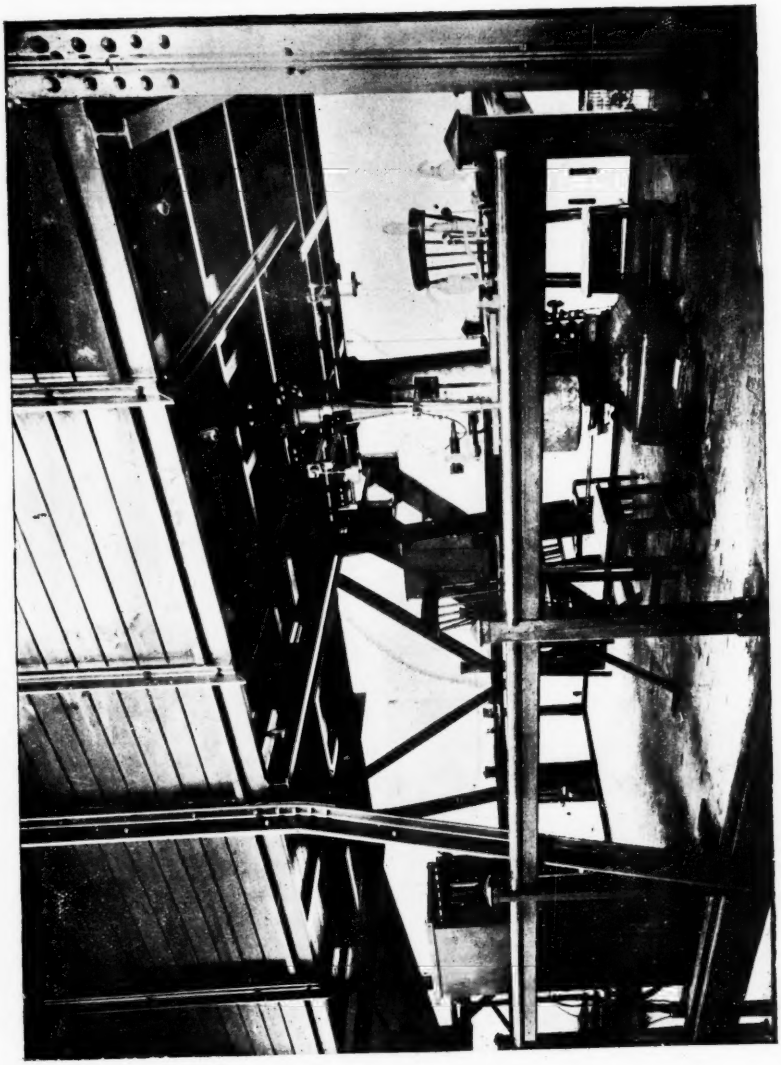


FIG. 12.
The Balance of the No. 2 7-foot Channel.

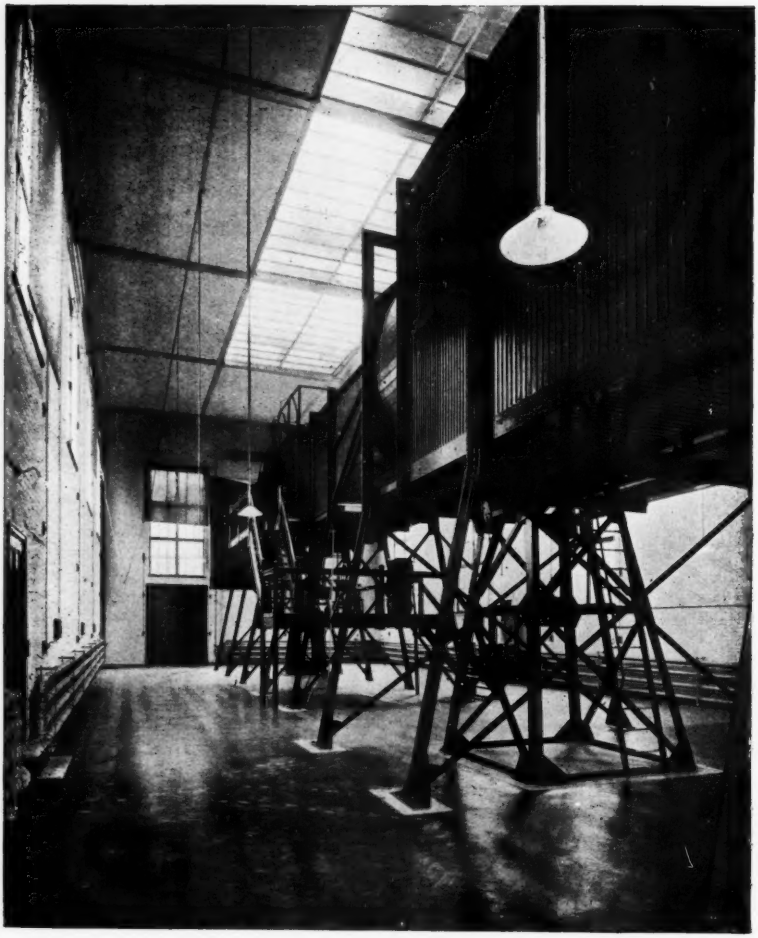


FIG. 13.

The No. 2 7-foot Channel: General Arrangement.

The large channel installed at the Washington Navy Yard is shown in Fig. 5. It is of the closed circuit type, the dimensions of the working section being 8ft. square and 33ft. long. It is fitted with a honeycomb at the entrance to the working section, some of the cells being closed to improve the uniformity of the

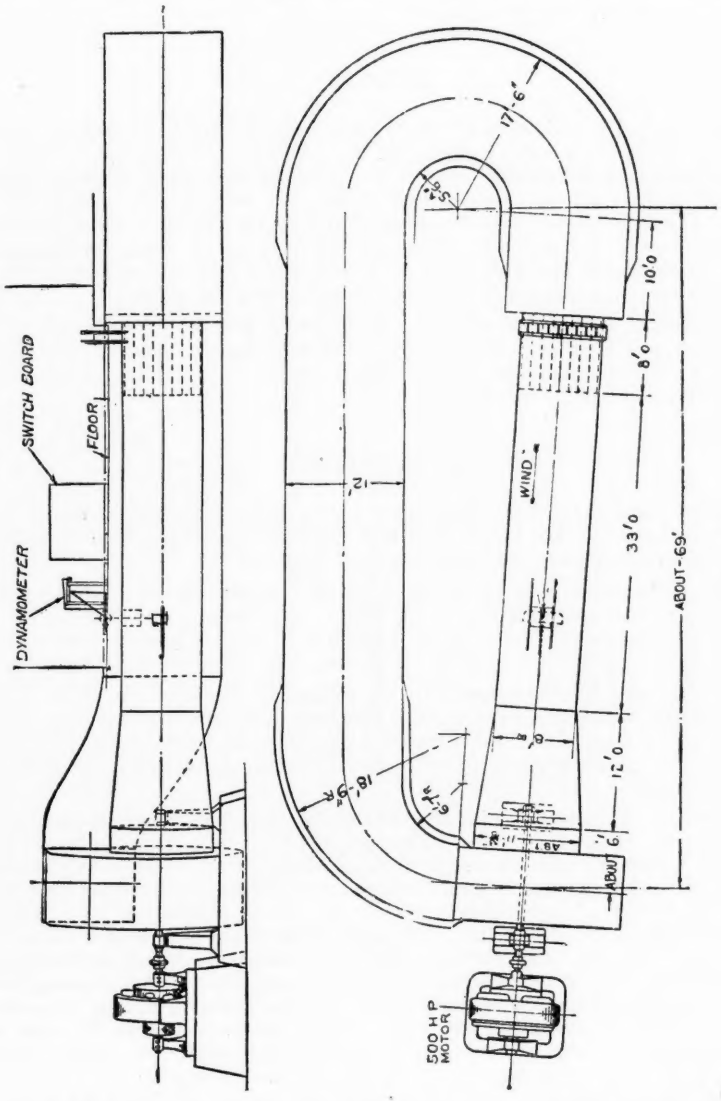


Fig. 5.
The Channel at the U.S.A. Navy Yard.

flow, which is said to be within 2% of the mean. The balance and motor control board are situated above the channel, the balance being similar to that used by Eiffel.

The current is produced by a 500-h.p. electro motor, driving a centrifugal fan; a maximum speed of 75 m.p.h. can be attained, but considerable heating of

the air takes place at this speed, and tests are usually carried out at 40 m.p.h. The velocity is measured by pressure tube anemometers, which have been calibrated against the N.P.L. standard.

A channel of the N.P.L. pattern has recently been erected in the Massachusetts Institute of Technology.

RUSSIA.

The principal experiments in aerodynamics which have been made in Russia are those conducted at the Institute at Kontchino, near Moscow,* under the superintendence of Riabouchinsky. The equipment includes a straight channel of circular section 4ft. in diameter and about 48ft. long, which is illustrated in Fig. 6. The air is drawn through the channel by a fan, which is belt-driven from an electro motor, and is returned through the building in which the channel is placed. A maximum speed of about 20ft./sec. is attained, and a balance, whose axis is horizontal, is provided for force measurements.

Experiments in this channel have, on the whole, been of scientific rather than of an engineering character, and include observations on the resistance of spheres, autorotation of plates, resistance of square plates, etc. The reports issued include several relating to propellers.

GREAT BRITAIN.

The principal aeronautical laboratory for model experiments in this country is at the National Physical Laboratory, and comprises five wind channels, enclosed whirling arm, small water channel, and two wind towers.

A 4ft. air channel is in use at the Royal Aircraft Factory in connection with the full-scale experimental work, which differs from those at the N.P.L., in that no distributor is used. The channel is located in a large airship shed, and no disturbance is caused at the intake due to the eddies from the airscrew.

The same modification is applied in the channel at the Royal Naval Air Station at Kingsworth, which has a section 6ft. (horizontal) by 4ft. In this case a four-bladed airscrew driven by a petrol motor is placed in the open air and the current is drawn through the channel from an airship shed. A speed of 100 miles per hour is attained.

A small wind channel was installed at the East London College in 1911, and is still in use for certain experiments. The equipment has been increased by the addition of a 4ft. channel, which is a copy of the National Physical Laboratory channels except that it is constructed of iron. The writer is indebted to Mr. Norman Piercy, who is in charge of the channel, for the following particulars. The balance differs from those at the N.P.L., the axis being horizontal, and includes one notably novel feature. Considerable trouble had been experienced with the pivot upon which the balance of the earlier channel was supported, and at the suggestion of Professor Macgregor Morris this pivot was discarded in favour of a metal diaphragm whose plane is vertical, and to which the balance is rigidly attached. The diaphragm is bolted between two stout metal rings, the motion of the balance being resisted by the flexural rigidity of the diaphragm.

With the diaphragm at present in use the limit of sensitivity is about 1/6000th of a pound. Greater sensitivity could be obtained by the use of a thinner diaphragm, but one objection to the method appears to be that the sensitivity cannot be readily changed in passing from one test to another.

*Kontchino Bulletin Fase, I., 1906.

The angle of incidence is varied by rotating the balance in a bearing, the outer part of which constitutes the attachment to the diaphragm. The lift forces are measured by weights hung on the beam of the balance; the drag forces are transmitted by a horizontal bell crank to another bell crank whose plane is vertical, and upon the horizontal limb of which the measuring weights are hung.

The maximum velocity which can be attained at present is 50ft./sec., but sufficient power is provided to attain 90ft./sec. when the driving arrangements have been modified.

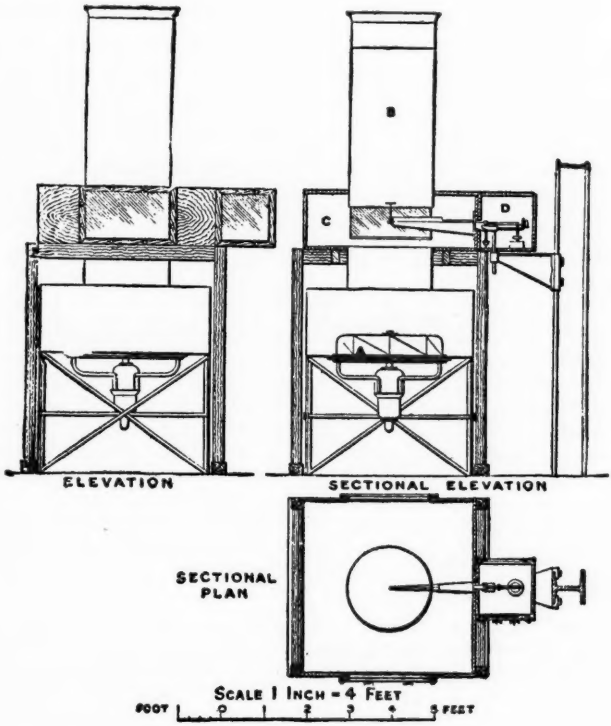


FIG. 7.
The N.P.L. 2-foot Channel.

There are many other channels in use in this country, but the author believes that the more important of them are copied from those at the N.P.L.

The remainder of the paper constitutes an account of the apparatus and methods which have been developed by the staff of the Aeronautics Division of the National Physical Laboratory.

THE CHANNELS OF THE NATIONAL PHYSICAL LABORATORY.

The first N.P.L. air channel, which was constructed in 1902, is shown in Fig. 7. It was designed by Dr. T. E. Stanton, F.R.S., and used by him for the experiments on the air resistance of plane surfaces. This channel consisted of a vertical tube 2ft. in diameter, through which the air could be drawn downwards

by a fan placed at its lower extremity. The air was delivered into the large engineering shop so that practically still air was continuously supplied at the intake of the channel. It is therefore not surprising that the steadiness of the flow was comparable with that of the newer channels. A balance was provided for measurement of forces along the wind only.

For measurement of velocity Dr. Stanton devised a pitot and static head of which the present laboratory standard (shown in Fig. 15) is the outcome; the only essential difference is that, for convenience, the tubes are now concentric, instead of some two inches apart, as in the original form. Much useful work was carried out in this channel, and it is still in service at the present time.

The Advisory Committee for Aeronautics was formed in 1909, and an extensive programme of work was laid down. The need of additional apparatus was at once felt, and it was decided to erect a new channel. This channel had its axis horizontal, and is shown diagrammatically in Fig. 8. The total length was 20ft. and the working channel, 4ft. square, was enclosed in a return channel 8ft. square. The air current was set up by a 6ft. Sirocco fan, driven by a belt from an electro motor, which drew the air through the working portion of the channel and delivered it to the return channel. Guide blades were provided at the fan outlet to correct the rotary motion of the air, and layers of wire gauze were introduced at the inlet to the test channel in order to improve the uniformity of the flow across a section. The velocity was measured by a pitot tube and Chattock tilting manometer, and reached a maximum value of 30ft./sec.

The balance was constructed in such a manner that simultaneous observations of lift and drag could be taken. The axis of the balance was horizontal, and for measurements of lift turned in ball bearings about a horizontal axis normal to its length. These bearings were carried in a fitting suspended on fine steel wires, allowing rotation of the balance through a small angle about a vertical axis for measurements of drag. The latter motion was transmitted to a right-angled bell crank whose plane was normal to that of the main balance arm. The horizontal limb of this bell crank constituted the drag beam upon which were placed weights to balance the wind forces. An oil dash-pot was provided which damped the oscillations of the two beams. One assistant observed the reading of the drag beam and another regulated the speed of the air current and observed the reading of the lift beam.

This channel was in use till the year 1912, and the whole of the experiments carried out up to that date were made in it or in the 2ft. vertical channel. The 4ft. channel was not, however, entirely satisfactory, the flow being too unsteady to allow experiments to be carried out to the high order of accuracy which was desired. This result was mainly due to two causes; in the first place the fan was of the centrifugal type which is now known to be unsuitable for this purpose. There were found to be large pulsations in the pressure, a feature which appears to be common to fans of this kind. The second cause, which was of less importance, was that the air was returned to the intake of the channel in a disturbed condition.

It was accordingly decided to undertake a complete investigation into the conditions which affect the uniformity of the flow.

The design of the N.P.L. channels in their present form was based on these model experiments, of which an account is given in the 1912-13 Report of the Advisory Committee for Aeronautics. The success of the experiments may be judged from the fact that the latest of these channels was made almost an exact copy of the first, the only modifications being of minor importance, which were suggested by experience as likely to facilitate the taking of observations or to improve their accuracy. The criterion by which the merits of the various arrangements was judged was the nature of the variations of pressure difference in a pitot and static tube of the standard N.P.L. pattern. The pressure was

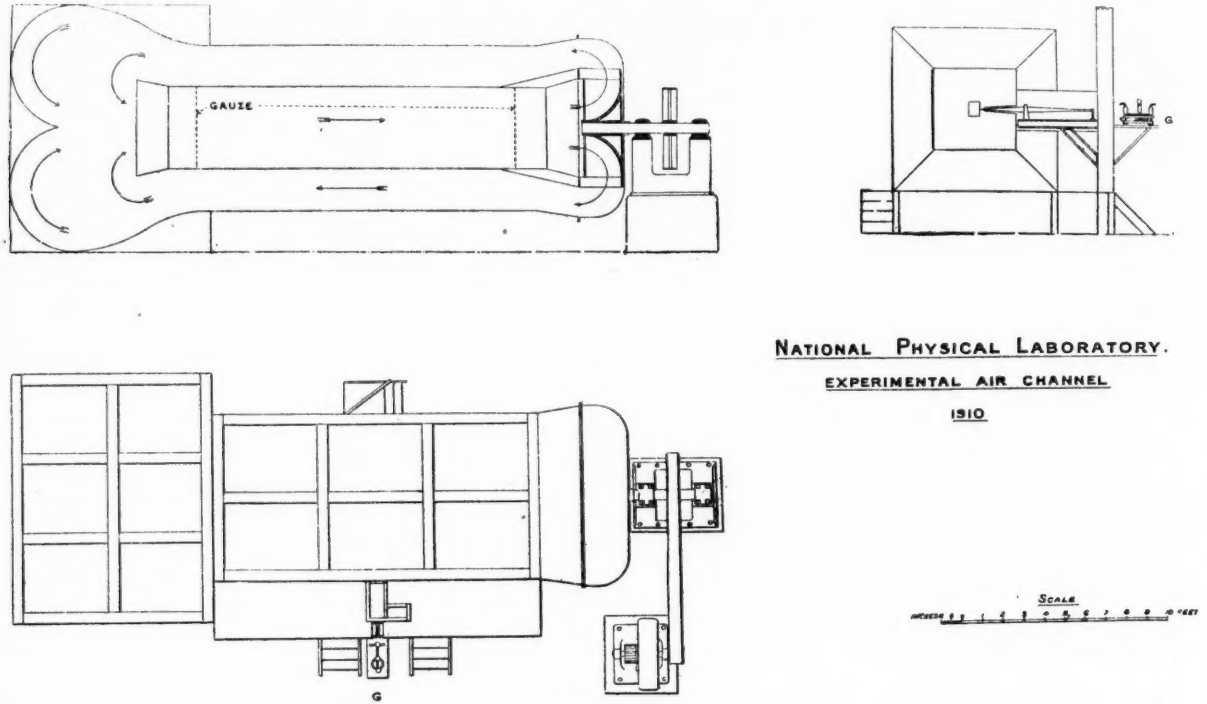


FIG. 8.

The Original 4-foot Channel: Early Type.

recorded by a special form of photographic gauge which was constructed for these experiments.

The model experiments were carried out with a channel 6ins. square, and this model was finally placed in a scale model of a bay of the engineering laboratory in which it was proposed to locate the actual channel.

A very exhaustive series of experiments was made with these models, and the following conclusions were finally arrived at:—(1) The air current should be produced by an airscrew of low pitch. (2) The air leaving the fan should pass into a distributer slightly larger than the fan and from three to four diameters long. The air should escape from the distributer through tubes of appreciable length (actually about 1.2in. in the 4ft. channels), which should distribute the air over as large an area as possible in constant quantity per unit area. (3) The smallest building in which such a channel may be housed to give satisfactorily steady flow is one whose dimensions are 6 × 6 × 15 channel diameters.

THE MODERN TYPE OF CHANNEL.

The new (or No. 1) 4ft. channel was constructed on these lines and is shown in Fig. 9. The channel, which has an overall length of about 54ft., is placed in a building 60ft. long, 50ft. wide, with an average height of about 20ft. This building was the existing engineering laboratory, and was larger than the size laid down by the model experiments. That size was, however, adhered to in constructing the 7ft. channel which was in view at the time the model experiments were being carried out. The No. 1 4ft. channel is provided with a trumpet intake and a honeycomb is placed in the parallel channel, A, near the entering end. The air passes through this honeycomb to the balance, which enters the parallel channel some 16ft. from the intake. At the end of the parallel portion a metal expanding piece is fitted, in passing which the section is changed from square to round. The circular part of the channel is very short, being just sufficient to house the airscrew, B, which is driven by a long shaft from an electro motor supported on the wall at the end of the channel. The air is delivered from the fan into the distributer, C, from which it passes at low velocity to the room.

A glazed door is provided through which models may be introduced, and a trapdoor is fitted immediately over the balance.

The fan has four blades 6ins. wide, and is capable of producing a current of 50ft. per second at 1,350 r.p.m. The power absorbed at this speed is 8-h.p., of which some 20% is lost in passing the honeycomb.

Regulating resistances are provided, and tests can be made at any wind speed from 20 to 50ft./sec.

The Balance.—The balance for the No. 1 4ft. channel is of entirely different design from that of the original 4ft., and is shown in Fig. 10. It was constructed with a view to carrying out the various complex experiments which were required as the study of the science progressed, and was arranged in such a manner that the interference of the supports with the model under test should be a minimum. Another difficulty was overcome which became more troublesome in the first balance as the size of the models increased, namely, the deflection of the balance; airship models weighing about 30lbs. have been tested on the similar 7ft. channel balance.

It is proposed to describe the first 4ft. balance and to refer later to some of the changes which have been made in the more recent balances.

The balance consists of two main parts, the lower of which carries the weighing arms and moment apparatus, and the upper of which projects upwards

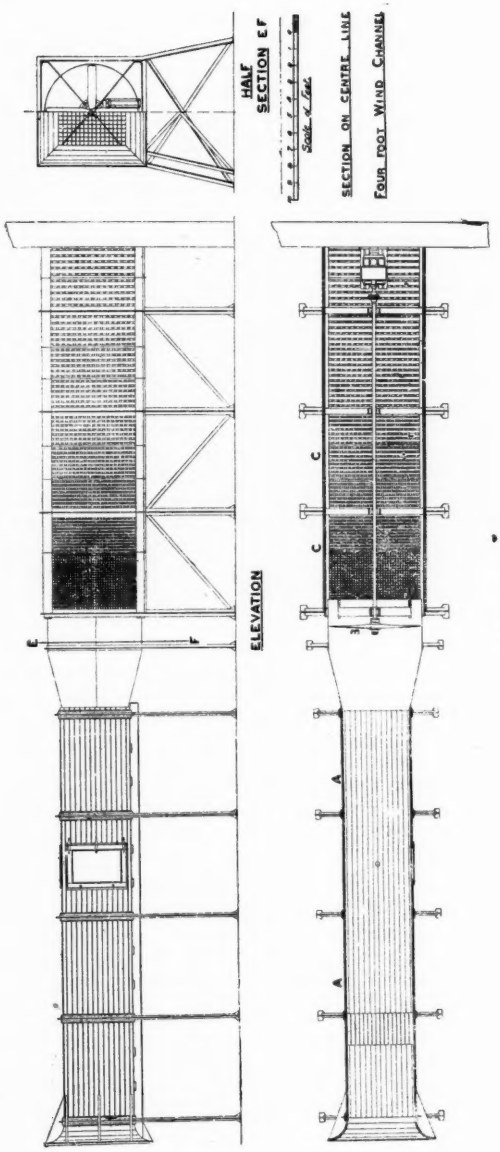


FIG. 9.

The No. 1 4-foot Channel: General Arrangement.

through the floor of the channel and carries the model under test. The portion of the balance inside the channel is shielded from the wind by a guard, which covers also a portion of the spindle. This guard should not be approached within about 3ins. of the model; in that position the interference due to it is usually negligible. The upper part of the balance can be turned upon the lower at C, and the model thus rotated through any desired angle about the vertical axis, from outside the channel, and without stopping the wind.

The balance is supported on a single steel point resting in a hollow cone. This cone is rigidly fixed to a heavy casting, which is firmly bolted to a cement bed and is perfectly free from contact with the channel itself. The steel point is at the intersection of the centre lines of the two weighing arms, which are set along and normal to the wind direction.

The balance has three degrees of freedom, and is arranged in such a manner that moments can be measured about the centre line of each arm and about the vertical axis of the balance. Thus, referring to Fig. 3, the reader is looking along the wind direction, and the drag forces on the model will cause a moment about the axis of the lift beam, L,* which is balanced by placing weights on the scale pan of the drag beam, D. In the same way a force across the wind causes a moment about the beam, D, which is balanced by placing weights on the scale pan of beam, L. A jockey weight is provided on each beam for fine adjustment. The third moment about a vertical axis was measured by means of the torsion of a wire, but this method has now been abandoned. There are two secondary arms placed diametrically opposite to the weighing arms, which carry balance weights, enabling the zero readings of the balance to be adjusted to values which will cover the range of forces to be measured. The arm opposite the lift beam is held by means of a strut and C spring in such a position that the drag beam is accurately along the wind direction. This strut, the point on which the balance rests, the centre lines of the weighing arms, and the points of support of the two scale pans, are all in the same horizontal plane when the balance is in its mean position.

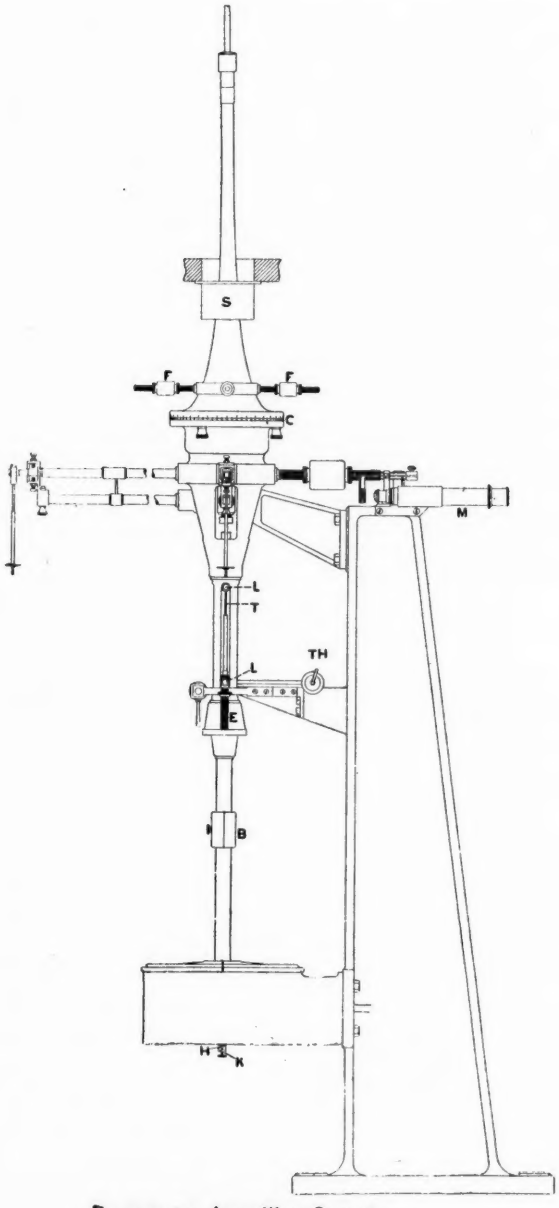
A movable weight, B, is provided for adjustment of the sensitivity, and additional weights can be placed on two studs, E, if necessary. A dashpot is provided at the lower end of the balance, and there is a clamp by means of which the balance may be locked in its mean position while adjustments are being made or the balance is out of use. Balance weights, F, are also provided in the upper half, by means of which the centre of gravity of the model and the part which rotates with the model may be brought into the vertical axis, about which the balance is turned. This adjustment prevents change of the balance zero when the angle of the model is varied. To prevent a stream of air flowing into the channel where the balance enters it, an oil seal has been fixed, which does not in any way interfere with the freedom of motion of the balance.

A force along the vertical axis of the balance was measured on an additional beam on which rested a rod passing through the trumpet of the balance and supporting the model, but this method has now been superseded.

A somewhat unusual arrangement has been adopted for detecting the departure of the balance from its zero position of equilibrium. The method of setting two cross-wires into coincidence is unsatisfactory, as it is not possible to place the cross-wires close together on account of the allowance necessary for angular motion of the balance during the measurement of moments about a vertical axis.

Parallax is, however, avoided by attaching to the beam a mirror bearing a line, and near it, but on the balance support, a cross-wire. The line and the

*This beam is called the lift beam from the common practice of supporting a model in such a manner that the lift forces act across the current.



BALANCE FOR 4 FOOT WIND CHANNEL
ELEVATION

FIG. 10.

cross-wire should be parallel, and with the balance in its zero position the cross-wire is adjusted till the line is midway between the cross-wire and its image in the mirror. The vertical distance between the wire and its image may be altered by adjusting the position of the eye, and this plan has been found to give higher accuracy than setting to coincidence. With a model whose weight does not exceed 2 or 3lbs. the balance is sensitive to .0001lb., and much less (.00001lb.) for very light models. For the highest accuracy the position of the line on the beam is observed by means of a microscope.

The Airscrew Balance.—The airscrew balance,* shown in Fig. 11,

Airscrew Balance for 4-foot Wind Channel.

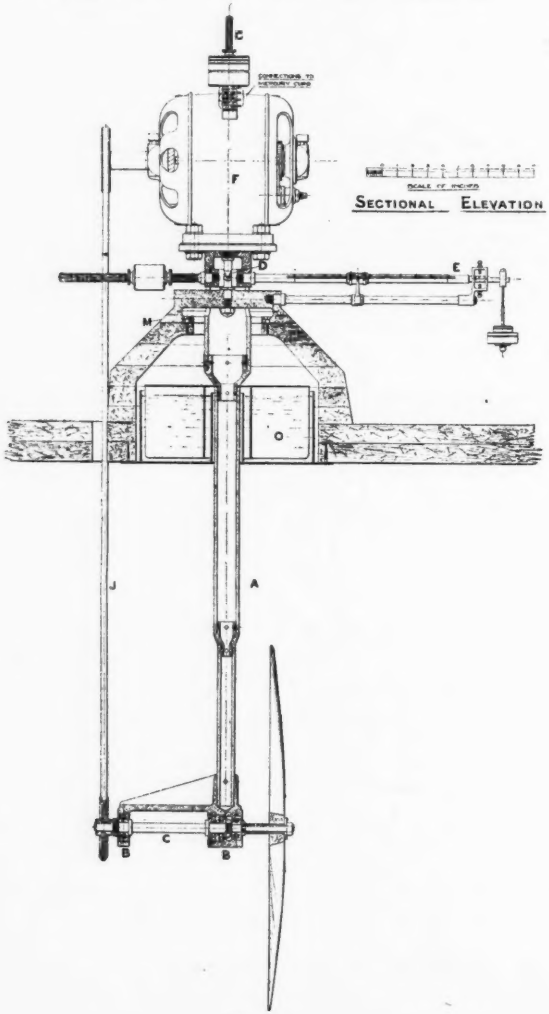


FIG. 11.

*Rpt. Adv. Comm. for Aero., 1913-14, p. 291.

differs very little from the main balance. It has two weighing arms and is supported on a single point, rotation about a vertical axis being prevented by a strut and C spring in the manner previously described for the main balance. A dashpot is provided to damp out oscillations, and as it cannot be placed further from the point of support than the roof of the channel, it is made to serve also as an oil seal. The speed of the airscrew is usually measured by electric signals from a toothed wheel driven from a worm on the airscrew shaft. In experiments in which it is important to maintain the speed at a predetermined value the worm gear is replaced by a commutator which enables a certain number of electric contacts (the number can be varied at will) to be made during each revolution. The pulsating current thus obtained is passed through an electrical frequency meter which gives an instantaneous indication of the speed to an observer at any distance from the balance. An electro motor for driving the airscrew is carried on the upper part of the balance, current being supplied through mercury cups in order to leave the balance perfectly free. The airscrew is driven by a belt passing through a slot in the roof, which allows the whole balance to be turned through an angle of 40° on either side of the position of symmetry. The arm, which projects downwards into the channel, carries at its lower end ball bearings for the airscrew shaft, the axis of which is coincident with the centre line of the channel. When the airscrew shaft is along the wind the thrust is measured on the arm parallel to the wind and the torque on the one perpendicular to it. When the shaft is inclined to the wind the thrust is still measured on the arm parallel to the airscrew shaft, but the arm perpendicular to the shaft measures the torque and the lateral force on the airscrew. These two quantities are determined from observations made when the model is inclined at equal angles on either side of the down-wind position. The torque will be given by the mean of the two readings and their difference will be equal to twice the lateral force.

The balance in this form has been described in the 1913-14 Report of the Advisory Committee for Aeronautics. A large number of experiments have been carried out since that date, and a new balance, the design of which has been modified in several important respects, is now in course of construction for the 7ft. channel.

LATER CHANNELS.

Since the No. 1 4ft. there have been constructed the 3ft. and No. 1 7ft. in 1914, and in the new aeronautics building the No. 2 4ft. and No. 2 7ft. in 1916.

The changes in design have been mainly in the balance; those in the channel consist in substituting slots for square holes in the distributor, and in turning back the trumpet mouthpiece till it touches the parallel part of the channel. The latter step was taken to prevent the formation of vortices, which were found to be formed at the edge of the original trumpet.

The speeds also have been increased, the highest values for the various channels being: No. 1 4ft., 50ft./sec.; 3ft., 60ft./sec.; No. 1 7ft., 65ft./sec.; No. 2 4ft. and No. 2 7ft., 80ft./sec. In connection with the high speed attained in the two newest channels it may be remarked that they are very noisy, and observers usually find it necessary to protect their ears with ear-defenders or cotton wool against the very intense vibrations which are set up over about 60ft./sec. The author is informed that the Kingsworth channel, in which a speed of 100ft./sec. is attained, and in which the fan is driven by a petrol motor, is much less noisy, and it has been suggested that the vibrations of the N.P.L. channels are due to the laths of the distributor.

The newer channels also have an additional honeycomb between the balance and the airscrew. This has the effect of entirely preventing spin of the air due to the rotation of the airscrew, but causes an appreciable increase in the resistance

of the channel. It is probable that guide blades of lower resistance would be equally effective.

Two important changes have been made in the design of the balance, namely, in the apparatus for measuring moments about a vertical axis and in the method of determining forces along that axis.

The method of measuring vertical force by a rod moving relatively to the balance has been abandoned in favour of the observation of the change in effective weight of the whole balance. No details of the arrangement can be given at present, but it may be stated that on the balance of the No. 2 7ft. channel forces can be measured with ease to 0.001lb., which is the 1/100000th part of the total weight of the balance. The balance of the No. 2 7ft. channel is shown in Fig. 12, while the illustration in Fig. 13 gives a clear idea of the general arrangement of the No. 2 7ft. channel.

ERECTING THE MAIN BALANCE.*

In order that certain conditions essential for accurate working shall be fulfilled, it is necessary that the erection of the balance be carried out with considerable care. The methods which are used for this purpose and to check the accuracy of workmanship will now be described.

Vertical Axis of Rotation in Moment Measurements.—When the balance is arranged for the measurement of moments about a vertical axis the strut which prevents motion about this axis when lift and drag are being measured is removed, and the lower extremity of the balance engages a centre, the position of which, in conjunction with the main supporting point of the balance, fixes the axis of rotation. The position of this lower centre is adjusted till the axis of the balance is vertical, when hanging weights on the lift and drag beams produces no moment about the axis of rotation. The sensitivity of the moments measuring apparatus renders the method easily accurate to an inclination of the axis of 0.005 degree. The axis of rotation in the N.P.L. channels is vertical to an accuracy of about 0.03 degree. The clamp which locks the balance should be arranged to hold it in approximately the same position when the lower centre is not in use.

Position of Axis of Rotation of Upper Part of Balance.—It is a matter of considerable convenience in measurements of moment about a vertical axis if the axis of rotation in changing the angle of incidence of the model coincides with that about which moments are measured. The relative positions of these two axes can be determined by fixing a point to the upper portion of the balance, adjusting it to lie in the axis of rotation of the upper portion, and then hanging from it a weight. If the balance remains in equilibrium when supported on a single point, the axis under examination is vertical, and therefore in coincidence with that about which moments are measured. If the balance turns under the weight, it must be returned to its zero position by changing the weights on the lift and drag beams and the process repeated with the point at a new height in the channel. Readings of the beams in the two cases enable the position of the axis to be determined.

The N.P.L. balances have been adjusted till the deviation at the centre of the channel does not exceed 0.01in.

Angle between the Lift and Drag Beams.—The ratio of the lift to drag in the test of an aerofoil is usually of the order of 17 as a maximum, and a very small error in setting the lift and drag beams at right angles may introduce a serious error in the measurement of drag. It

*See Rpt. Adv. Comm. for Aero., 1912-13, p. 59 *et seq.*

has been shown* that in order to avoid errors in the drag measurement exceeding 1% when the ratio of lift to drag is 15, it is necessary that the angle between the beams shall be 90° to an accuracy of ± 0.05 degree. If the linear distances between the scale pan centres and the point of the balance can be accurately determined, the most direct method of measuring this angle is to compare the sum of the squares of these lengths with the square of the distance between the two scale pan centres. It was inconvenient to measure directly the lengths of the beams, and a temporary weighing arm was fixed to the upper part of the balance for the purpose. This was set in turn parallel to the lift and drag beams and a weight of 1lb. moved through an accurately measured length. The moment thus caused was measured on the beams and the distance of each scale pan from the point of support of the balance deduced. The method of calculating the angle, referred to above, can now be applied. The angle between the beams in each of the N.P.L. balances is 90° with an error not exceeding 0.02 degree. The error in the drag measurement will not exceed ½% due to this cause, and will usually be much less.

Determination of Wind Direction and its Relation to the Position of Beams.— The accuracy with which it is necessary to set the beams along and across the wind direction is the same as that with which the angle between the beams is required to be a right angle. An error in the two cases has the same result, viz., to include a component of the lift in the drag measurement.

The wind direction has been found to be parallel to the walls of the channel to an accuracy of 0.1 degree, but it is determined by the experiment which gives the angle between it and the drag beam.

The method which has been used for this determination is to mount an aerofoil in the balance, with its span vertical, and measure the lift and drag over the usual range of angle. The model is then rotated through 180° about the wind direction (thus reversing the direction of the lift) and a second set of measurements taken. The mean of the two sets gives the true value of the forces, and their difference enables the errors of wind direction and balance setting to be determined.

An actual set of observations which was obtained in calibrating one of the channels is shown in Fig. 14. The two lift curves differ by an angle of 0.2 degree, the datum line to which the aerofoil was set being half this amount in error from the true wind direction. The drag curves, however, cannot be made to agree by movement of one of them along the abscissae; the difference is due to the

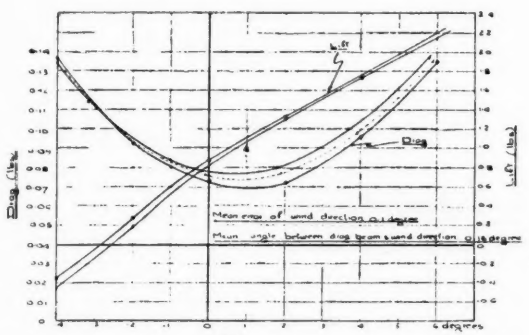


FIG. 14.
Setting the Balance Arms.

*Rpt. Adv. Comm. for Aero., 1912-13, p. 63.

drag beam not being set along the wind direction. As would be expected, since the difference in the drag curves is due to a component of the lift, the two drag curves cross at the angle of zero lift. The angle error can be estimated by moving one curve along the angle base by the amount indicated by the lift curves (0.2 degree) and reading off the drag from each curve at several angles. If L is the lift at any angle and α the angle between the beam and the wind direction, then half the difference is equal to $L \sin \alpha$, and α can be deduced. In this case α was equal to 0.16 degree. The balance was turned through this angle by adjusting the length of the strut which prevents motion about a vertical axis, and the experiments repeated, using the wind direction indicated by the lift curves. The forces should now be in agreement for the two presentations of the model. The drag curve obtained after the adjustment had been made is shown dotted in the figure, and is in close agreement with the mean of the two previous drag curves.

MEASUREMENT OF WIND VELOCITY.

A pitot and static pressure tube of the type used by Dr. Stanton was adopted for measurement of wind velocity. The head in use at the present time is the same in principle, but has been arranged in the manner shown in Fig. 15 for convenience. This type of head has been tested on the whirling arm at the Laboratory,* and the difference of pressure was found to be $\frac{1}{2}\rho V^2$, while that in the static pressure tube was equal to the pressure of the undisturbed air in the building. The accuracy was limited by that of the test, which was of the order of 0.1% on the velocity.

It was at first hoped to measure the velocity in the channel during a test by mounting this head some 3ft. (100 diameters of the vertical tube of the head)

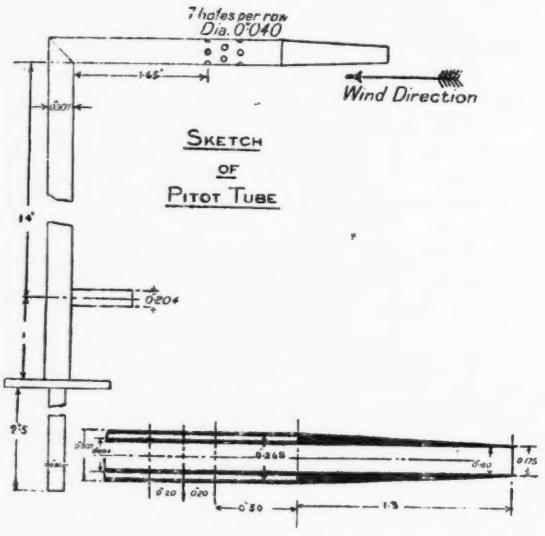


FIG. 15.
The N.P.L. Standard Pressure Tube Anemometer.

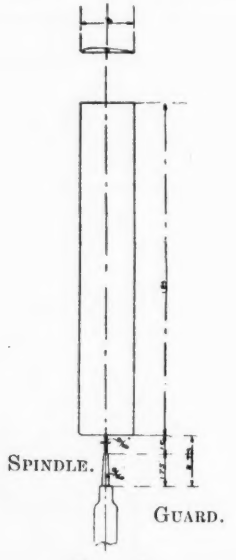


FIG. 16.
An Aerofoil on a Spindle.

*Rpt. Adv. Comm. for Aero., 1912-13, p. 35.

upstream of the model. This plan was abandoned, as it was found that there was a region in the neighbourhood of the balance about 1½in. wide in which the velocity was 10% below the mean. The alternative method which was adopted consisted in measuring the pressure difference between a hole in the side of the channel and the free air in the room. In order that the pressure in this hole may not be changed by the presence of the model, it should be located sufficiently far upwind of the balance to be in front of the model. The pressure difference is greater than $\frac{1}{2}\rho V^2$, on account of the pressure drop in passing the honeycomb and early part of the channel. The pressure difference, however, varies, as V^2 and the channel is readily calibrated by placing the standard anemometer over the balance. This calibration can be made with an accuracy of about 1% on V^2, and should be repeated at stated intervals. The pressure difference is measured on the Laboratory tilting manometer, which has been fully described elsewhere.*

This manometer is in general use at the N.P.L., but it suffers from one defect which is not present with the inclined tube type of gauge. It is necessary that the tilting manometer shall have continuous attention during the time it is in use, and in the case of a failure of the electric supply the observer can seldom shut the tap before the surface is ruptured. It is then usually several minutes before the gauge can be used again, and it is liable to change of zero for a longer period.

Experiments have been carried out at Massachusetts Institute of Technology, U.S.A., with the "Krell" type of inclined tube manometer,† and the conclusion arrived at was that if properly constructed and used the gauge could be regarded as an instrument of precision suitable for wind channel work. It requires calibration, and may be compared with the tilting manometer which is an absolute standard. The inclined tube gauge appears to be sufficiently accurate for use on a channel, where the fluctuations usually limit the accuracy attainable. It cannot be too strongly stated that a steady electrical supply is a matter of the highest importance if accurate results are required. In the writer's opinion there is no doubt whatever that, with channels of the type in use at the N.P.L. and with the usual conditions of electrical supply, the accuracy of the observations depends entirely on the steadiness of the wind speed. If a channel which normally works on the ordinary supply circuits is connected to a storage battery, the improvement in the accuracy of the experiments and the reduction in the time taken is most marked. If a storage battery cannot be provided, a Tirill regulator makes a fairly efficient substitute. The author has had no experience of automatic speed regulators; the only one of which he has seen a description (in use on the channel at Göttingen) is operated by the pressure difference on either side of the fan. In order to avoid "hunting," it appears that it would be preferable to adopt a device (possibly operated by centrifugal force) which would regulate directly on the speed of the airscrew, since the variations here are presumably the source of speed variations in the channel.

COMPARISON OF THE CHANNELS.

Dimensions.—The differences between the 3ft., No. 1 4ft., and No. 2 4ft. channels are small, and confined to improvements in the convenience of working in favour of the latter. The woodwork of the two 4ft. channels is the same, and though no comparative measurements of steadiness have been made, there appears to be little to choose between the two. The maximum speed of the No. 2 4ft. is 80ft./sec., while that of the No. 1 4ft. is 50ft./sec.

The No. 2 7ft. channel is not an exact copy of the No. 1. The buildings in which they are housed are of approximately the same size, but as the newer

*"Engineering," Sept. 12, 1913.

†Smithsonian Misc. Col., Vol. 62, No. 4, p. 34.

channel is supported on steel frames instead of concrete columns, the obstruction to the flow of air returning to the intake of the channel is appreciably less.

The channels differ in the manner shown in the following table of approximate values :—

	No. 1, 7ft.	No. 2, 7ft.	No. 1, 4ft.	No. 2, 4ft.
Overall length	86ft.	86ft.	52ft.	52ft.
Length of parallel portion ...	41ft.	41ft.	25ft.	25ft.
Intake to balance	20ft.	25ft.	6ft.	6ft.
Length of distributer	35ft.	32ft.	21½ft.	21½ft.
Length of cone to airscrew ...	10ft.	13½ft.	4ft.	4ft.
Angle of cone (total internal) ...	20°	20°	30°	30°
Diameter of airscrew	10ft.	11.5	5½ft.	5½ft.
*Effective pitch/diameter ...	0.50	0.7	0.60	0.75
Revs. per minute at 60ft./sec. ...	1000	910 (50ft./sec.)	1350	1300
Power absorbed at 60ft./sec. ...	48 h.p.	56 h.p. (50ft./sec.)	8 h.p.	14.6 h.p.
Revs. per minute at 80ft.sec. ...	—	1210	—	1500
Power absorbed at 80ft./sec. ...	—	155 h.p.	— (70ft./sec.)	23.3 h.p.

The No. 2 7ft. channel has been found to be less steady than the No. 1 7ft., in spite of the increased area available for the returning air. The difference is possibly due to the increase in the pitch of the airscrew or to the reduced length of the distributer.

Cost.—A few particulars of the cost of erecting the wind channels may be of interest. The figures given were estimated to cover replacement under present conditions in the event of loss by fire, and are based on the actual cost of erection under the supervision of H.M. Office of Works :—

	No. 2 7ft.	No. 2 4ft.
Total	£2,120 ...	£590
The more important items are :—		
Motor	300 ...	60
Honeycombs (2)	75 ...	35
Balance	350 ...	250
Woodwork	1,000 ...	80
Airscrew	35 ...	50

We may now pass to the consideration of the methods which are used for supporting models in the channel.

METHODS OF SUPPORT.

There is perhaps no more difficult part of an investigation into the wind forces acting on a model than that which is concerned with the increase of resistance due to the supports. The difficulty depends to a large extent on the kind of model which is under test. If the resistance of a sphere, or a square plate in normal presentation, was being investigated, it is unlikely that any appreciable error would be introduced by the assumption that the correction to be applied is given by a measurement of the resistance of the support in the absence of the model. In the measurement of the resistance of a "streamline" body, however, an entirely different state of affairs exists. The resistance of an airship model 6ft. long and 0.5ft. in diameter is in some cases less than 1/10th of that of a square plate whose area is equal to that of the maximum cross-section of the airship model. Even though such a model is supported on a

*Effective pitch is calculated from the airspeed in the channel just before the airscrew (neglecting increase of velocity due to inflow) divided by revs. per min.

spindle about 0.3in. in diameter, an error amounting in some cases to as much as 20% of the model resistance would be introduced if this method of measuring spindle resistance were adopted. In the test of some models several alternative methods are available. Thus in experiments on aerofoils the method which is usually adopted is to mount the model, with its span vertical, on a spindle screwed into its end.* An alternative method (which was adopted by Eiffel) is to support the model with its span horizontal on a spindle screwed into, for instance, its under surface, the support being constructed in such a manner that the angle of incidence of the aerofoil can be varied. In this case the support can be made of "fair" form, while in the former one it turns with the model, and is necessarily circular. If a low-resistance aerofoil whose span is 18ins. and chord 3ins. is under test, the relative values of the spindle resistance in the two cases of span vertical, and span horizontal, are about 60% and 110% of the minimum drag. The relative size of spindle and aerofoil in the former case is shown in Fig. 16. These high values are caused by the length of spindle which must be exposed in order that the presence of the guard may not interfere with the flow round the model. It is therefore seen that the resistance of the spindle is nearly doubled when the span of the model is horizontal, and though this is bad enough it does not constitute the most serious objection to the method. The methods of evaluating the resistance of spindles have recently received a good deal of attention, and it has been shown that while, in the case of the spindle in the end of the model, the increase in resistance is not very different from that of the resistance of the actual spindle, there is much "interference" between the model and the spindle when the latter is attached to the under surface of the aerofoil.

It is therefore desirable, whenever possible, to test aerofoils with spindles in their ends; in cases where this cannot be done (such as experiments on wing tips), great care must be taken in the determination of the resistance due to the support.

In experiments on streamline bodies the resistance due to the supporting spindle is even greater. One example was that of a model of an airship envelope inches long supported on a spindle inch in diameter, used for the experiments which were carried out in the small water channel in 1909.† The length of spindle immersed in the water was 2.3 inches and its resistance, determined in the absence of the model, was approximately half that of the spindle and model together. The actual increase of resistance, due to the presence of the spindle, was undoubtedly much greater, due to its "interference" with the flow round the model.

STABILITY.

The question of stability of aircraft has been examined mathematically in considerable detail, the methods of developing the equations being laid down in Bryan's "Stability in Aviation." These methods have been developed by Bairstow, with the assistance of various members of the aeronautical staff of the Laboratory. In Report 77‡ the theories have been applied to the flight of an aeroplane, and were investigated for the case of an airship in 1916.

It is proposed to examine the methods which have been employed in measuring in the wind channel the various forces, moments, and damping coefficients for models of actual aeroplanes. For the purpose of stability calculation the axes are supposed to be fixed in the machine, and the nomenclature

*Rpt. Adv. Comm. for Aero., 1912-13, p. 77.
†Rpt. Adv. Comm. for Aero., 1909-10, p. 70.
‡Rpt. Adv. Comm. for Aero, 1912-13, p. 135.

which has been adopted at the Laboratory (which differs from that of Bryan) is as follows:—

Name of axis.	Symbol.	Name of force.	Symbol.	Name of angle.	Symbol.	Name of moment.	Symbol.
Longitudinal	X	Longitudinal	X	Roll	ψ	Rolling	L
Lateral	Y	Lateral	Y	Pitch	θ	Pitching	M
Normal	Z	Normal	Z	Yaw	ϕ	Yawing	N

If the centre of gravity is at O, the positive directions of the axes are as follows when the machine is in rectilinear flight in a horizontal plane:—OX in the direction opposite to that of flight, OY to the left (*i.e.*, to port), and OZ vertically upwards. Forces are positive when acting along the positive directions of the axes, angles and moments are positive when turning occurs, or tends to occur, from OX to OY, OY to OZ, or OZ to OX. Angular velocities about the axes OX, OY, OZ are represented by p, q, r, and linear velocities along them x, y, and z.

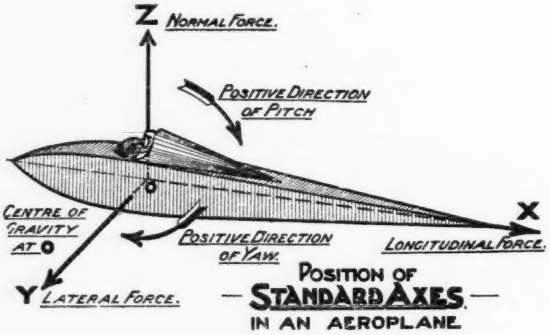


FIG. 17.

The rate of change of one quantity with regard to another of which it is a function is represented, in the usual manner, by writing the symbol for the latter as a suffix to that for the former. Thus the change of pitching moment due to pitching is represented on the system of axes chosen, by M_q. The writer's experience has shown it to be desirable, if mistakes are to be avoided, that a system of axes, such as the one quoted and represented in Fig. 17, should be adopted for all wind channel work, and rigidly adhered to. The angle scale on the balance should be numbered in such a manner that rotation from X to Y increases the reading; the micrometer screw of the main moments apparatus should be graduated so that a moment which tends to turn the model from X to Y gives a reading greater than the zero. If the angle of pitch of a model is to be changed by rotation about a vertical axis, it should be mounted if possible with its under surface facing along the axis of Y. Forces, angles, and moments will now have their correct signs, except for normal force, for which the sign must be reversed. Care must be taken to correct the signs if the model is mounted in the reverse way, as is usually done in determining yawing moments on an unsymmetrical model.

We may now consider the determination of the quantities which must be known in order that the criteria of stability of a machine may be calculated. The first operation will be to mount the model in the channel in the

usual way and determine the equilibrium forces on it. These results enable us to calculate (on the assumption that the wind forces vary as the square of the velocity) the resistance derivatives for variation of wind speed.

The derivatives for variations of velocity along the axes Y and Z are given by the curves of normal and lateral force for angles of pitch and yaw. If the angle base is degrees, the value of Z_w/U or Y_v/U is obtained by multiplying the slope of the curve near the origin by 57·3 to convert degrees to radians and dividing by the square of the wind speed.

It remains to measure the resistance coefficients due to oscillations through the equilibrium position, which have been called Rotary Derivatives.

The experimental determination of these quantities has already been described* in connection with tests on an aeroplane model, and though the apparatus has been modified, the same methods are in use at the present time.

Measurements were made by the method of observing oscillations, and only five of the more important derivatives were considered. These were :—

The Pitching moment	due to	Pitching	...	M_q
,, Yawing	,,	,, Yawing	...	N_r
,, Rolling	,,	,, Rolling	...	L_p
,, Rolling	,,	,, Yawing	...	L_r
,, Yawing	,,	,, Rolling	...	N_p

The first three can be determined by observations of the damping of a natural oscillation, but the last two require that the model shall be oscillated about one axis while it is free to oscillate about another at right angles to it. The method was to set up an oscillation about the axis of yaw (or roll) and to adjust the period about the axis of roll (or yaw) till resonance was obtained; the required data can be deduced from a knowledge of the amplitude of the oscillations. The determination of these derivatives by forced oscillations was found, however, to be a matter of some difficulty, and the results can only be regarded as preliminary.

The remaining three derivatives—L_p, M_q, and N_r—were determined in the wind channel by observation of the damping of natural oscillations. The method for M_q and N_r was to mount the model on the balance in the same manner as for an experiment on the forces, the balance being free to rotate about a vertical axis. The motion was controlled by springs which maintained the oscillations for a period of from 20 to 40 seconds against the damping due to the wind forces and the friction of the apparatus. The damping of the oscillations was recorded photographically for several wind speeds. The reduction of the results consists in plotting the $\log_e$ of the double amplitude on a " number of swings " base for each wind speed (including zero). These lines are approximately straight for the part of the curve over which the amplitude is reduced from its maximum value to half, and the logarithmic decrement is consequently determined from this slope. If the slope at zero wind velocity is subtracted from the slope at each of the other velocities and the result divided by the periodic time (T) at that wind speed, we get values of $\mu_1/2I$ where μ_1 is the damping due to the wind and I the moment of inertia. If each value is divided by the appropriate wind speed (U), we find the damping to be nearly proportional to the speed. I can be calculated from the equation

$$T = \frac{2\pi}{\sqrt{\frac{k_1}{I} - \frac{\mu_0^2}{4I^2}}}$$

where T is the periodic time at zero wind velocity, k_1 the moment due to the apparatus, and μ_0 the damping due to friction. We can now obtain values of

*Rpt. Adv. Comm. for Aero., 1912-13, p. 172.

μ_1/U, and if we neglect change of the coefficients with scale and speed we can calculate BM_q/U and CN_r/U by multiplying by the fourth power of the ratio of the dimensions of the actual aeroplane to those of the model, B and C being the moments of inertia in pitch and yaw respectively.

Since L_p is due almost entirely to the wings it can be calculated with sufficient accuracy and this plan has been adopted for recent work on aeroplane stability; in the experiments of 1912 special apparatus was constructed for oscillating the model about its longitudinal axis.

SCALE AND SPEED EFFECT.

In considering the application of model results there is one important correction which it is necessary to apply to the great majority of experiments in a wind channel; it is that for change of size and speed between the model and the actual machine. It has now been well established that for what may be called totally submerged bodies, such as aircraft or torpedoes, where the type of motion is determined by the viscosity of the fluid, we may write, if compressibility does not affect the problem,

$$R = \rho v^2 l^2 f\left(\frac{vl}{\nu}\right)$$

where R is the resistance to forward motion, v the velocity, l a dimension of the body, and ρ and ν the density and kinematic viscosity of the fluid. If the form of the function is unknown, we can only be sure that the motion in an experiment on a model will be similar to that on the actual machine if the value of (vl/ν) is the same in the two cases. This condition is usually unobtainable in wind channel tests, as both the size and the speed are much higher in practice; in the case of rigid airships the value of vl for the actual ship is some 200 times that in the model test. By carrying out tests in water ν can be reduced to 1/14th that of air, but the experimental difficulties then become very great and in most cases outweigh the advantages of an increase in the value of (vl/ν). Experiments on full-scale machines are admittedly extremely difficult, and it is only recently that they have been carried out on aeroplanes. It is hoped that in the near future resistance experiments on full-size airships will be made.

Experiments on models over the greatest possible range of speed appear, in many cases, to indicate that the power of the velocity which the resistance varies at is not very different from 2 at the highest value of (vl/ν) obtainable. If R/aV^2, then $f(vl/\nu) = 1$, and we can calculate the forces on the actual machine directly from our model experiment.

A very large amount of data has been obtained in testing the aeroplanes which are being constructed for our naval and military forces, and comparisons of the greatest value are now possible between the results obtained on models and the performances of actual machines. The writer believes that the time is not far distant when the design of new machines will be essentially based on the results obtained in experiments on small-scale models in a wind channel.

It was the author's good fortune to be associated for some years with Mr. Leonard Bairstow, F.R.S., who became superintendent of the Aeronautical Division shortly before he left the Laboratory. The progress which has been made was due in a very large measure to his personal ability and to the sympathetic encouragement which led to such close co-operation between the members of the staff who worked under him.

In conclusion, the author desires to thank the Advisory Committee for Aeronautics for permission to publish the information contained in the paper; he is also indebted to Sir Richard Glazebrook, F.R.S., for the facilities he has granted in connection with the preparation of the diagrams and lantern slides.

PROCEEDINGS

SECOND MEETING, 53rd SESSION.

The second meeting of the Session was held at the Royal Society of Arts, on Wednesday, November 21st, when Mr. J. R. Pannell, F.Aë.S., read a paper on "The Wind Channel, its use, and correction factors for using the results." The chair was taken by Sir Richard T. Glazebrook, C.B., D.Sc., F.R.S., F.Aë.S., Director of the National Physical Laboratory, who briefly introduced the lecturer.

(A report of Mr. Pannell's lecture appears on page 211).

A discussion followed.

The CHAIRMAN said he had listened with much pleasure to the very interesting paper read by Mr. Pannell. The lecturer had had a wide experience in wind channel work, and had, considering the disadvantages under which he laboured, made the most of the subject. It was not possible now to tell to a meeting, even of a society like this, all that we could put before them in happier times. He was convinced that in aeronautical work wind channels were of great importance. As they gathered from the lecturer, they had made a very early beginning at the National Physical Laboratory, and there are now a great number of wind channels in the country, as firms everywhere were realising the importance and utility of experiments conducted with them. The Laboratory were always glad to give to manufacturers all the assistance that was possible.

With regard to the paper, if Mr. Pannell had limited it to its early portion and the description of the wind channels in this country and abroad, even this limited paper would have been valuable and well worth while both reading and hearing. But Mr. Pannell had gone further and had done well in drawing our attention to the methods by which these experiments were conducted. It was indeed necessary to emphasise the extreme care and accuracy needed in wind channel work. It was clear to him that working with a wind channel on a larger scale was no easy matter.

Mr. Pannell's short reference to the work that had been done at the Laboratory on stability brought into mind the valuable work done by Mr. Bairstow in this connection.

The value of the wind channel was every day more and more recognised, and he thought he was disclosing no secret in saying that at present the Laboratory was hard at work with all the channels it had completed.

There are a large number of experiments being made with both model and real aeroplanes. Sir Richard here referred to the formulæ used by Mr. Pannell which were based on the calculations in Newton's "Principia." One class of critics urged that working with models was a very different thing from actual experience with full-sized aeroplanes, but by the use of this formula it was an easy step from the model to the real thing. All that was necessary was to extend the range of experiment and thus obtain a fuller knowledge of the relation between the model and the real thing. This emphasises the need for the care and accuracy which Mr. Pannell had described.

Of course there are still discrepancies which are now being investigated, experiments being made both with models in the channels and with real machines. He was convinced that much honour was due to those who were carrying out these experiments, and he had listened to Mr. Pannell's paper with real interest and appreciation.

Lieutenant-Colonel MERVYN O'GORMAN said he was pleased that the wind

tunnel was accepted as a suitable subject for discussion. The model work was valuable as the basis for evolving full scale machines. One of the greatest difficulties they had was what had been foolishly called the struggle between the rule-of-thumb man and the theoretician. The latter name was applied to the men who made models and the former to the men who made aeroplanes. It was a pleasure to find the people who made aeroplanes were welcoming those who made models and told them how to do it, and also it was a pleasure to learn what a large number of wind tunnels there were in England.

Mr. L. BAIRSTOW said a good deal of the work of the N.P.L. had been covered by the paper and by the Chairman's remarks. They concerned themselves to a large extent with the direct application of wind channel results to full scale work. If the readings as they were obtained from the wind channel were increased in proportion to the scale of lineal dimensions designs on that basis were very sound. British designers who took a large departure from existing practice liked to feel that they had the support of model experiments behind them. He thought the British designer had made more use of the results of model experiments than had the designers of any other country. It was always true that in detail full scale experiments could not supply the necessary information for the design, as it was not possible to take a machine to pieces in the air in sufficient detail to inform the designer which part of the machine was giving trouble. Such analysis could only be done by models. Practically all the defects of the full scale machine could be reproduced in the model. That was rather different from taking a model and using it for the purpose of production. There might be an error in the prediction of speed of 5, 10, or more per cent., but the model would indicate the type of error that was being made and was therefore valuable.

Models were also useful to assist in the education of aeronautical engineers. Actual experience of measuring forces on a model was valuable in teaching students and designers how to think. The result of adding the resistance of the aerofoil and spindle was different from that of taking the parts separately. Probably the only attempt that could be made at a mathematical investigation would start from the model end, because of the facilities one had for controlling the experiments. After the war he thought every university would have a wind channel for training aeronautical engineers. Model construction was essential to the progress of the industry.

Captain H. GRINSTEAD: I do not think that it can yet be said that the model results can be applied directly to the full-scale aeroplane. Predictions of performance based on model experiments do give roughly correct results, that is, the error is probably not more than 5 to 10 per cent. on speed, but in order to be of use in designing, and in helping to decide between two alternative designs, greater accuracy is required.

The difference between actual performance and that predicted from model results was forcibly brought to our notice in two ways. Firstly, aeroplanes lost speed at altitude much more than was predicted, indicating that the resistance at the larger values of the lift coefficient was greater than that supposed. Secondly, on high speed aeroplanes in which the lift coefficient at top speed was below that at which the model drag coefficient was a minimum, an increase of weight was not accompanied by the expected increase of speed.

The exact responsibility for these discrepancies is difficult to locate as in the experiments on the full scale aeroplane it is very difficult to determine the effect of small variations of any one part, but from a long series of careful experiments it is indicated that the scale effect is on the wing characteristics.

It was mentioned that the effect of a small spindle on the upper surface of the model wing caused a very large difference in the resistance of the wing, and in the discussion the effect of the strut on the full-scale wing has been referred to

in this connection. The comparison cannot, however, be directly made as we know that there is a very large scale effect on small wires, whether of circular or of streamline section, over the range of speeds obtained in the wind channel, and it is therefore reasonable to suppose that the conditions on the full-scale strut and wing are quite different from those on the small wire and the model wing. The results of full-scale tests so far indicate that the effect of the presence of a strut on the wing resistance is much smaller than is indicated by the model.

Much work is being done to investigate the differences between model and full-scale results, but in the full-scale investigations it is very difficult to obtain accurate results. It would be far better if we could have a very large wind channel where wings, etc., could be investigated in full-scale size and at the speeds at which they operate in actual flight. Such a channel would of course be expensive, and would absorb a large amount of power, but would not cost either in its construction or its maintenance more than perhaps two or three complete aeroplanes, and would soon pay for itself by removing the necessity for having a considerable number of aeroplanes employed on the full-scale investigation.

Professor MACGREGOR MORRIS said after working on the subject at the East London College for some years, they were given the opportunity, through the kindness of the Chairman, of getting out designs of a new tunnel on the same lines as those at the N.P.L. Mr. Bairstow helped them very much, and the tunnel had been at work for some time.

Could Mr. Pannell give any information on the pulsations that occurred along the wind channel—whether the pulsations were greater in the direction of the axis or at right angles with it? His experiments led him to believe that longitudinally, the pulsations were much less than at right angles to the direction of the air. Taking two points apart one found the pulsations were three times as great at right angles to the axis. Had it been shown by experiment that if the same model were treated in a 4ft. and in a 7ft. wind channel the lift was not the same at the same angle? When the model was tilted there must be a down stream, and that must strike the walls of the channel, and he thought it was more likely to produce that effect in a small than in a big channel.

Mr. NORMAN PIERCY said the results obtained in the wind channel at the East London College were more or less in line with those obtained in other tunnels, and had been more or less realised in practice. That referred to the lift-drag experiments.

For experiments on the centre of pressure they had resuscitated an ancient method of setting the pivots at a certain point and balancing the model at that position, finding the wind currents and finding the angle at which the model sets itself. They then measured the moments of the lines of force about two points outside and below the tunnel. It had been brought into line four or five times, and once only there had been a small difference between the two curves at small angles. Theirs was a horizontal balance, but if they had had the time and money it would probably have been of the N.P.L. type. In that small tunnel they found it more important to have the honeycomb between the model and the propeller than in front of the model. They put an additional honeycomb in front of the propeller, which improved the velocity of the distribution. When they started the new 4ft. channel they found, in testing a small model right way up and upside down, that the difference in the lift-drag ratio was about 12 per cent. After a good deal of manœuvring they located the cause of the trouble. It was caused by the eddy or change of direction of the air caused by a board about 8in. high, on its edge, about 4ft. in front of the end of the trumpet of the tunnel. When the board was removed the readings were symmetrical and the wind currents were horizontal. With regard to the resistance of spindles, if a spindle was attached to the lower surface of an aerofoil the lifting force was along the edge of the spindle, and the

continuation of that distortion to the model was only caused by the direct forces at right angles acting at the same moment. There was no force across the tunnel caused by the lift in that case, so he would have thought the spindle could be much diminished in thickness across the tunnel when its resistance would be much less, the guard tubes being further away from the model than in the case where the model was held by the spindle in its end. He would have thought the resistance of a stream-lined spindle of suitable length, when decreased in maximum thickness, would have been less than .3 of that of a round one. Had any experiments been made to determine the maximum depth of section of model holder which could be used without causing any great interference between the model holder and the model, if that interference could be reduced if the thickness of the spindle were reduced to .07in.? He thought that was the thickness of some he experimented with at the college.

Mr. FAGE: From the excellent lecture which we have had this evening, and also from the Chairman's remarks, it is clear that every endeavour is made at the National Physical Laboratory to conduct the aerodynamic experiments with great accuracy, and perhaps one may be inclined to ask whether data sufficiently accurate and reliable could not be obtained more quickly with less elaborate apparatus. I remember reading some time since an article in the technical Press in which the writer, whilst fully appreciating the value of the experiments made at the National Physical Laboratory, was inclined to believe that the future aerodynamical laboratories of private firms would probably obtain experimental data of good enough accuracy much quicker with less exact methods of experimentation. It seems to me that the speed at which experimental data can be obtained depends on the experimenter and his familiarity with the experiment, and also on the apparatus. The best results are most quickly obtained when elaborate apparatus is placed in the hands of the highly trained experimenter, who is thoroughly at home with the pitfalls of the experiment, and perhaps what is more to the point, such an experimenter knows the value of his measurements. I am not decrying the value of rough-and-ready apparatus—many people, owing to lack of opportunity and finance, have to be contented with such equipment—but I do think there is a real danger when rough-and-ready apparatus is put into the hands of an experimenter of the rough-and-ready type.

Naturally, at a national institution, such as the Laboratory, it is of paramount importance that a high standard of accuracy should be consistently maintained, because the results of the experiments are recorded and often used in international comparisons.

In conclusion, I should like to say that even if a really genuine attempt is made to secure good accuracy, it does not always follow that the desired result will be attained—a very good reason why we should always strive for something better.

Mr. R. DE VILAMIL: There is much to be said in favour of the wind tunnel, but this Society is not, however, to degenerate into a "mutual admiration society." It is well to know what is to be said against it. I take up, therefore, the position of *avocatus diaboli*.

In the first place I take exception to the lecturer's loose employment of the word "velocity," which he uses as if synonymous with speed. Velocity is a *vector* quantity, and hence it involves "direction." In the jargon of Quaternions, "speed" is the *tensor* and "direction" is the *versor* of this *vector*. To speak of a "velocity" of 10 miles per hour is to talk nonsense.

It may be said that the lecturer is in the fashion and in accord with the classical text books. If we turn to the Chairman's book on "Dynamics," we see that, in the second chapter, "velocity" and "speed" are accurately defined, and the difference between them in very clearly explained. After this we find the

words velocity and speed used almost indiscriminately, the result of which is certainly very confusing.

The lecturer does not say so in words, but he certainly infers that it is a matter of indifference whether the body is in motion in air at rest or the air is moved past the body at rest.

I think I can confidently assert that *an accelerated velocity is not the same as a uniform velocity.* I therefore sincerely hope that stationary models will *not* be applied to experiments with ships' models. When mathematics and physics are driven in tandem, the mathematics should *always be in the shafts.*

It has been stated that in a frictionless liquid there would be *no resistance*—this is taught is every text book; but we find Newton saying that the resistance would vary *as the square of the velocity* and as the density of the liquid. Lord Kelvin's paper on *coreless vortices* in a perfect fluid may be also referred to. The resistance is clearly in accordance with Newton's statement. Also, what is called the " Rayleigh-Kirchoff flow " in a perfect liquid is, very clearly, *not* a " no resistance flow." If, however, we go to fundamentals, and refer to dynamical similarity, we see that the resistance is *accurately in accordance with Newton's dictum.* As to the expression " fluid friction," a term much in fashion in aeronautics, Lord Rayleigh, not very long ago, said that no one knew what it meant, but that it was a " very convenient expression." It certainly is, for it is a kind of " funk hole." If one is in want of an argument one can always attribute any unaccountable result to fluid friction.

The accuracy of the speeds, as measured by the use of the Pitot's tubes, appears to be very questionable. This was brought to notice by Lord Rayleigh (A.C.A. 1910-11):—" In many of the experiments *v is known only indirectly* from the indications of the Pitot's tubes, in which *the measured difference of pressure is taken to represent the square of the velocity. . . .* I see no *a priori* reason *why* v^2 *should be represented thus, any more than by the total force on the plate* exposed to the wind."

More than 50 years ago M. Dupré showed *experimentally* that the equation $v^2 = 2gh$ was not accurate *for air,* and " should be abandoned for high velocities, and that one should only employ it for ordinary velocities, or up to 40 or 50 metres *when an extreme exactitude was not necessary.*"

I am inclined to think that the speed (for air) is *always* less than that given by calculation; and Dupré's experiments appear to confirm this view.

It may be urged that we have compared the results obtained by the use of the whirling machine with those obtained in the tunnel and they are " very similar "—I do not suppose it will be pretended they are *exact.* This is a most unsound argument. You are comparing two accelerated motions. Doubtless, if the arm of the whirling machine were of the *proper length,* you might even get *exactly the same results.*

Of course Langley said and proved by $X + V$ that the *error due to circular motion,* with an arm of 30 feet length and a square moving plate of 2ft. 6in. side, was only about *one-fifth of one per cent.;* quite a negligible quantity. I am afraid the mathematician was here wrong again. He *assumed* that *because the speed was uniform, therefore the velocity was uniform.* Making proper allowances, the error will be found to be of the order of 10 *per cent.;* certainly not a negligible quantity.

The wind tunnel has a great defect which it shares with the whirling machine; it shows a very marked (so-called) " dimensional effect." This increase of pressure *on unit surface,* as the dimensions of the plate increase, is firmly believed in by most of our leading experts. If, however, we believe in the principle of similitude we know that it *must be wrong.* In mathematics you must accept

all or nothing; not only all the assumptions *explicitly made,* but *all the logical deductions that lead from them.*

Now, if the results obtained from whirling machine experiments are properly corrected it will be found that the (apparent) " dimensional effect " disappears. I think that there is no reasonable doubt that if suitable corrections were applied to the wind tunnel results, the same remarks would apply—but of this I have no personal experience; I do not know how to correct them.

It may be accepted, I think, that any " dimensional effect " observed is very strong evidence that the *velocity was not uniform.* It may be pointed out that there are two sets of experiments, one by M.M. Cailletet et Colardeau and the other by M. Eiffel, which are *very similar,* but yet have a small difference between them. Both sets were made on plates falling freely from the Eiffel Tower. The apparatus for both was designed by M. Eiffel, and both sets of experimenters were quite first class. The small difference between these sets was that M.M. Cailletet and Colardeau's plates were weighted with *small weights,* and they consequently attained what are called " terminal velocities "—*after which the velocities were uniform.* M. Eiffel's plates were accelerated by *very heavy weights,* and were accelerated *up to the end of the fall—the velocities were not uniform;* he specially says they were not.

As we should expect, the " dimensional effect " was *very marked* in M. Eiffel's experiments; whilst it was *completely absent* in those of M.M. Cailletet and Colardeau, where the velocity was uniform. This absence of dimensional effect was specially remarked upon by M. Eiffel.

I think that these experiments tend to show, very strongly, that the " dimensional effect " is all moonshine.

Having pointed out some of the defects of the wind tunnel, let me refer to the manner in which Mr. Pannell interprets the results, what he calls the " corrections to be applied for change of scale and speed."

Mr. Pannell put on the blackboard the formula

$$R = \rho l^2 v^2 f\left(\frac{vl}{v}\right)$$

as representing the formula of resistance of bodies in water or air. The lecturer did not say so explicitly, but this is, obviously, what is commonly called " Lord Rayleigh's formula." Unfortunately the function has been turned upside down so as to make nonsense of the formula.

" But," Mr. Pannell may say, " it is frequently used in this form at the National Physical Laboratory. This is, unfortunately, quite true. In some of the papers issued by the A.C.A., the formula is *quoted as Lord Rayleigh's,* correct reference is given to the paper *and page,* and then it is *copied incorrectly!* The correct formula (omitting constants) is

$$R = \rho l^2 v^2 f\left(\frac{v}{vl}\right)$$

Mr. Pannell tells us that we may take this for the formula for the resistance of torpedoes *and aircraft.* I accept its accuracy for bodies moving in water—*considered as an incompressible fluid.* It is *not correct,* however, for the resistances of bodies moving in air, or other *compressible fluids.* At speeds of 100 feet per second the results are about 7 per cent too low; and at speeds of 100 miles per hour the error is of *the order of* 10 *per cent.* The formula tells the truth—*but not the whole truth.* You *must add another term, in consequence of the compression.* The fact has been thoroughly well recognised at the National

Physical Laboratory that there *must* be a term in the formula involving the *third power of the velocity*.

I may be reminded that Mr. Lanchester has said (A.C.A., 1909-10, page 33) that "this error does not become of sensible magnitude till velocities are reached *considerably in excess of half the velocity of sound*." Experiment shows, *most conclusively*, that it is not correct.

To continue, Mr. Pannell says: "If the form of the function is unknown," etc. But the form of the function *is* known (for liquids) and it is employed in the N.P.L. It is not necessary to go to "authority" for this; anyone with an elementary knowledge of dynamical similarity can, by the use of *very simple algebra*, find this out for himself. It will be seen to work out as

$$R = \rho l^2 v^2 \left(\frac{v}{vl}\right)^n$$

But, as n is not known, Lord Rayleigh generalised this as $R = \rho l^2 v^2 f(R/vl)$. We must be careful to remember, however, that $f(R/vl)$ is only intended to mean $(R/vl)^n$, where n is not known. It means that resistance *increases directly as some power of* R. This formula is *fundamental* and cannot be disputed.

The lecturer says, when $R \propto v^2$, then $f(vl/R)$—or "more correctly" $(R/vl)^n$—$= 1$. I think this is rather putting the cart before the horse. I would prefer to put it, when $n = 0$—*i.e., when there is no viscosity*—$(R/vl)^n$ becomes $= 1$, and consequently, $R \propto v^2$; or, more fully, $R \rho \propto v^2 l^2$ (as Newton said it should).

If the resistance is *purely viscous*, it is clear that $n = 1$; for we know, from experiment, that the resistance varies *as the viscosity* simply, and *not as any other power of this viscosity*. We then get $f(R/vl)$ or $(R/vl)^n = R/vl$.

Since the *total resistance* is composed of that caused *by the viscosity*, plus that which is *independent of the viscosity*, it is clear that it may be expressed as

$$R = \rho l^2 v^2 \left\{\frac{v}{vl} + 1\right\}$$

We see here, again, that the first term in the binomial is *the only one which involves viscosity*, and that $f(v/vl)$ can only $= 1$ when we *neglect the resistance due to viscosity*.

If we read this equation properly we shall see how *ridiculously unimportant* the resistance due to viscosity generally is. v is a very small number, 0.0005, for air. The binomial will therefore become $\{.0005/vl + 1\}$. If the value of $vl = 1$ (a very low value), the *error* caused by *neglecting viscosity* will be about 1/20 *of one per cent.*

If, however, $vl = 200$—a very conservative number for a full-sized aeroplane, where v alone may be nearly 200—the error caused by this neglect will be about 1/4,000 *of one per cent.*!

On the other hand, if the model tested is *very small*—say, a very fine wire—where vl might be equal to 1/200, the error caused by assuming that $R \propto v^2 l^2$ *might be* 10 *per cent.*

These remarks will show the absurdity of attaching any importance to the viscosity—*kinematic*, or other—of air, when referring to the resistance of full-sized aeroplanes. What is important, however, is to remember Newton's dictum (Book II):—"And when the resistance of bodies in non-elastic fluids is once known, we may then *augment this resistance a little in elastic fluids*, as our air." Newton does not say "how much," but experiment shows that it is about 7 per cent. for each 100 feet of speed, up to 100 per cent., at about 1,400 f.s., after which the resistance increases *as* v^2 *only*.

I think that the corrections required for converting the results obtained from experiments with small models in a wind tunnel—the accuracy of which results I have no means of testing—to results to be expected from full-sized aeroplanes, is by no means as easy and simple as the lecturer has tried to make us believe.

Mr. PANNELL, in reply to discussion, said that numerous experiments had been made to determine the effect of testing models in the channels of different sizes, and it had been shown that if proper precautions are observed good agreement can be obtained. He had no information as to relative intensity of pulsations in the wind in two directions at right angles to each other.

Mr. Norman Piercy's account of the change in wind direction due to a board outside the channel was very interesting. The spindle used in supporting an aerofoil with its span horizontal had been reduced to very small dimensions, considering that it contained a device for adjustment of angle. The principal part of the resistance was caused by the interference of the small plate to which the model was attached. The values of 60 per cent. and 110 per cent. for spindle resistances represented the worst cases; for high resistance aerofoils they would be much less. As regards the honeycomb it must be looked upon as a necessary evil; it was evil because it caused a considerable reduction of speed, but it was necessary, particularly at the intake of the channel, in order to obtain the desired degree of uniformity in the velocity distribution. Some reduction of resistance might be effected without any objectionable result by substituting guide blades for the honeycomb near the airscrew.

In reply to Colonel R. de Vilamil, the author did not claim that experiments on a whirling arm of a similar nature to those of Langley on square plates were accurate. There was, unfortunately, an error introduced due to the action of centrifugal force on the "dead water" region at the back of the plate. He did, however, firmly believe in the accuracy of the pitot tube, which a test on the whirling arm had showed to agree to 1/10th per cent. with the pressure equation for such a tube in a perfect fluid. With reference to experiments on square plates, he would like to point out that the experiments of M. Eiffel were in good agreement with those of Dr. Stanton on 2 inch square plates in the wind channel and 10 foot square boards in a natural wind; the author is unacquainted with the experiments of MM. Cailletet and Colardeau.

With regard to Colonel de Vilamil's objection that in the formula

$$R = \rho v^2 l^2 f\left(\frac{vl}{\nu}\right)$$

"the function has been turned upside down so as to make nonsense of the formula," he and the author evidently did not understand the same thing by an indeterminate function; if f was *indeterminate* it was a matter of indifference which way up the function was written. In the author's opinion Colonel de Vilamil is definitely wrong in his statement that, in Lord Rayleigh's formula for fluid motion in the general form given above, (ν/vl) is only intended to mean $(\nu/vl)^n$ where n is unknown.

The formula

$$R = \rho v^2 l^2 \left(\frac{\nu}{vl} + 1\right)$$

is only applicable, as Colonel de Vilamil shows, to a case where the effect of viscosity is small. It should be noted, however, that in calculating values of R for different values of vl/ν the bodies must be *exactly similar*. This formula could not apply to the resistance of fine wires where the effect of viscosity is found experimentally to be large.

General RUCK moved a vote of thanks to Sir Richard Glazebrook and to the author of the paper, which was carried unanimously.

ABSTRACTS.

THEORY OF THE AIRSCREW.

Professor Georges de Bothezat has contributed to "Aviation" an introductory article on the theory of the airscrew which defines the terms and hypotheses used in his conception of the phenomena associated with screw propulsion. In it the author, late of the Polytechnic Institute, Petrograd, gives the outlines of a new theory of the airscrew.

The term "Relative pitch" is adopted as a fundamental parameter and defined as the pitch of an element of the screw blade, measured by taking the pitch of the blade element as unity. The "Specific function" is the relation of the work of the thrust to the work of the torque applied to the screw axis.

An illustrative diagram gives the general analytical condition of all states of work for a typical screw. In this a curve is drawn for the values of "Relative pitch" as abscissæ against the "Specific function" as ordinates. The portion of the curve between the abscissæ $x = 0$ and $x = 1.0$ is marked "Airscrew" corresponding with the ordinary propeller. This portion of the curve approaches an asymptate $x = 1.1$ (approx.) in the direction of the negative axis and is marked in this portion of the curve as "The Intermediate Brake State." From this abscissa onwards the ordinate decreases from $+\infty$ to a value of 1.4 at $x = 1.3$, when it increases gradually to a point at $x = 2$ marked as "The Standing State." This branch of the curve is marked "Turbine." For small negative values of relative pitch the "Specific function" has two nearly equal negative values, represented by a loop with a cusp at the origin, and corresponding with the "1st Brake State of Work." From near the end of the loop defining this part of the curve it is discontinuous from about $x = -0.3$ to -0.6, and is then represented by a straight line to a point with co-ordinates $x = 1.5$, $y = 1.6$ (approx.), which corresponds to "The Standing State." This straight line is defined as the "2nd Brake State of Work" and the loop as "The Vortex Ring State of Work."

In the article considerable emphasis is laid on the phenomenon discovered by the author in a purely analytical manner. It is named "The Vortex Ring Working State," and is represented by the dotted discontinuous part of the curve. In explanation, he imagines the screw working in the state of brake, as is the case for a large negative relative pitch, and considers the progressive lessening of its translational speed. Under these conditions a moment arrives when a surface of discontinuity is formed in the wake of the screw across which the fluid will not flow. Directly after its formation the surface of discontinuity divides into two surfaces and a vortex ring, the axis of which coincides with the axis of the screw and appears in the space thus formed. The two surfaces of discontinuity which enclose the vortex ring move progressively apart, and a moment arrives when one of these surfaces crosses the space swept by the blades of the screw. The moment corresponds to the change of direction of the stream of fluid which flows across the plane of the screw, and at once the screw tends to make an infinite number of revolutions.

Referring to the positive portion of the curve, the "Specific function," after reaching a maximum, diminishes rapidly and, passing through nil value, comes to a short interval of breakage, which passes asymptotically to the turbine work of the screw. In this latter interval the "Specific function" represents the inverse of the efficiency of the turbo-motor. After passing a minimum which corresponds to the maximum of the turbo-motor efficiency, the "Specific function," by a parabolic branch, quasirectilinear, disappears into infinity, corresponding to the stoppage of the screw in a current which is directed on the screw.

After reference to various authors on hydrodynamics and to the work done on discontinuous motion by Kutta and Karman, Professor Bothezat elaborates his own conception of dealing with fluid motion problems, which he calls the "Empirico-theoretic" method. In general, this may be represented as follows:—"All the space in which a hydrodynamic phenomenon has played is divided into two sorts of regions. In one of these the hydrodynamic resistances are, so to say, concentrated, in the other they are absent. The hydrodynamic resistances once experimentally determined, the connection between the two sorts of regions is established by means of the general theorems of mechanics and hydrodynamics, the phenomena which take place in the second sort of regions being considered as under the laws of perfect fluids." This conception is applied to the theory of the screw, but not elaborated in any detail. ("Aviation," May 15, 1918.)

WIND AT VARIOUS HEIGHTS.

The results of pilot balloon observations made at the Zentral-Anstalt für Meteorologie und Geodynamik, Vienna, in the years 1911-1914 have been analysed by von Berger and A. F. La Roche. The total number of ascents dealt with is 996, of which 284 exceeded 5 km. and 79 exceeded 9½ km. The data at the disposal of the authors were the mean velocities for ½ km. stages, published by the Zentral-Anstalt for each ascent. The stages or zones have been numbered from I. to XX.; the lowest stage numbered I. is from ground level, 200 m. to 500 m. Each of the others covers 500 m. The winds above 10 km. are not discussed. The results are set out in tables and in diagrams. Some of the results are given below:—

(1) The average speed of the wind varies from 5.4 m/s in stage I. and 7.8 m/s in stage II. to 11.8 m/s in stage XX. Increase of wind speed in going from one stage to the next occurred in about two-thirds of the cases, the proportion being as high as 80 per cent. for the step from stage I. to stage II.

(2) The maximum wind-speed recorded at any height on any day during the month is given much prominence in the tables. Such a maximum usually occurs just before the balloon is lost to sight, a fact which should be borne in mind in the discussion. In nine months out of the 48 the maximum occurred in stage V. (though never in stage IV.). The favourite direction for the maximum was W.N.W., which is credited to 10 months. The highest maximum, 39 m/s, occurred in September, 1912. The height above ground at which it was found is not stated.

(3) Taking all ascents together, the favourite direction for the wind in stage I. was W.; in stages II. to VIII., W.N.W. or N.W., and in stages IX. to XX., W.N.W. or W. On the average, winds within 90° of W.N.W. are about four times as frequent as winds in the other two quadrants.

(4) In an investigation of the steadiness of the wind the following definitions are adopted:—

Gerader Kurs (Straight Course).—A change in direction of not more than 11° 15′ (presumably between one stage and the next).

Biegung (Bending).—A change in a single quadrant, not more than 90°.

Wendung (Reversal).—A change between 90° and 180°.

Schlinge (Loop).—A change of more than 180°.

The cases of "*Schlinge*" are presumably those indicated by footnotes in the original reports.

For stage II., *Gerader Kurs* is entered in 54 per cent. of cases, *Biegung* in 42 per cent., *Wendung* in 3 per cent., and *Schlinge* in 1 per cent. For stage X. the corresponding percentages are 70, 28, 2, 0, and for stage XX. 79, 19, 1, 1. (J. Van Berger and A. F. La Roche, "Osterreichische Flug-Zeitschrift," Feb. and Mar., 1918.)

AERIAL WAVES AND WIND DIRECTION.

On October 1, 1917, a disturbance, presumably due to an air wave, was reported at places near the coast of Holland. Doors flew open and shut, pictures swung on the walls, and windows clattered. It is stated that, according to the official report from the Meteorological Institute at de Bilt, the disturbance was to be attributed to an explosion which occurred at a munitions factory in the North of England. Accepting this explanation of the phenomenon, the author regards it as evidence of a strong current from N.W. in the upper air; this current is identified with the one which carried the German airships over France when returning from a raid on England on October 20, and is referred to as the summer monsoon prolonged into the autumn. (W. Krebs, "Osterreichische Flug-Zeitschrift," Jan., 1918.)

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Aviation and the War. Discussion of the training of aviators; also some remarks on the classification of machines. (C. F. Lee, "Journal of the Washington Academy of Sciences," April 19, 1918.)

The Effect of an Aeroplane Rudder in Flight. Describes methods of finding the moments about the centre of gravity of aeroplanes of different length due to rudders of different aspect ratios under varying angles of deviation. The results are expressed in the form of tables and curves. (Karl H. White, "Aviation and Aeronautical Engineering," May 1, 1918. 4 Figs.)

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ABRIDGMENTS OF RECENT PATENT SPECIFICATIONS (AERONAUTICS).

COMPILED BY MR. H. T. P. GEE, PATENT AGENT.

115,704. S. E. Saunders, The White House, East Cowes, Isle of Wight. May 24, 1917.

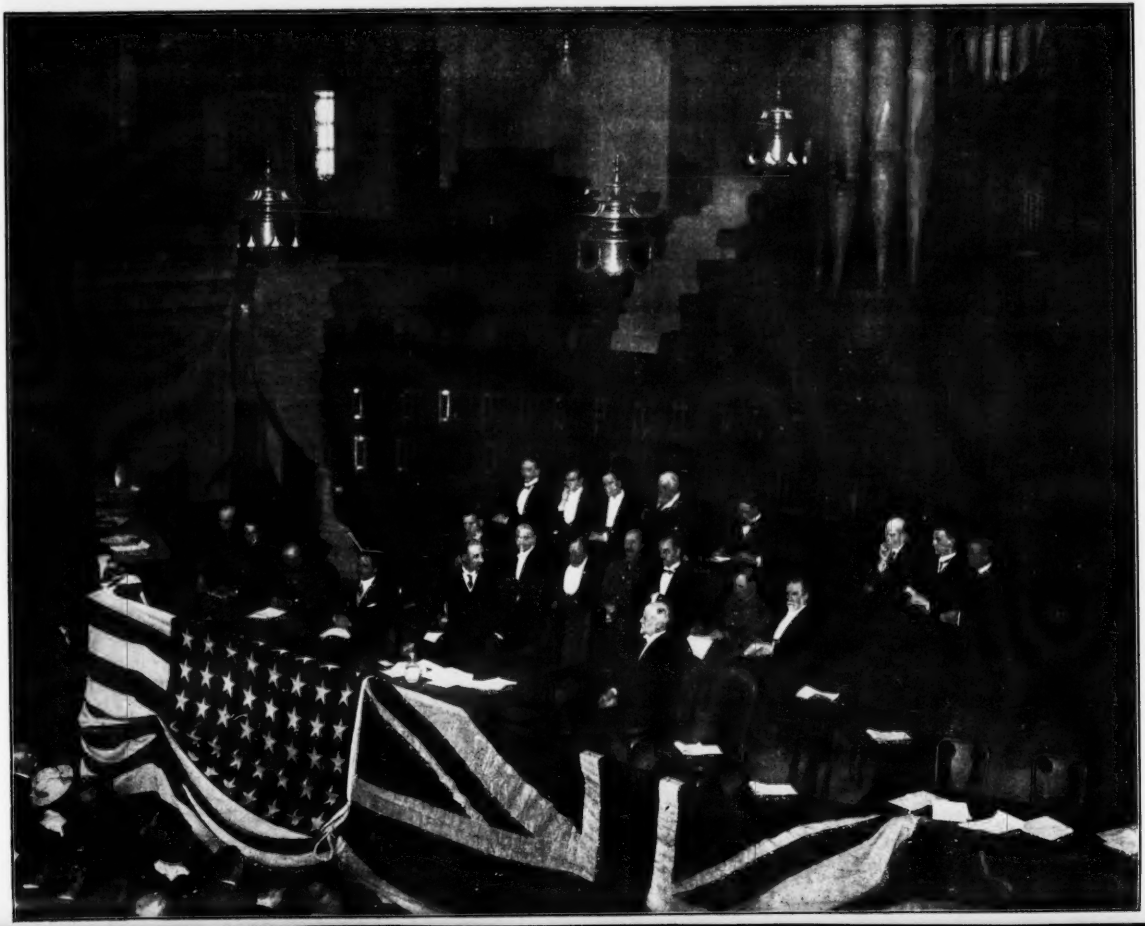
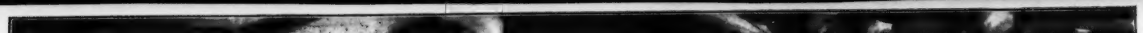
Planes, Arrangement of.—The planes of an aeroplane are made detachable from the fuselage as an integral structure by forming a gap in the wing structure which is slipped over the fuselage from above or below or over one end. In one form the inner struts of the plane structure carry a saddle-piece which fits over the fuselage, the ends of the lower spars being secured in sockets on the fuselage by pins or bolts. In a modification the two halves of the plane structure are suitably hinged, and the spars of the lower planes have spigot ends provided with lateral pins adapted to engage bayonet slots in sockets on the fuselage. The sockets are simultaneously turned to lock all the spars in position by interconnected levers. In another modification the fuselage is introduced from above the planes. The fuselage has a supplementary framing, and interfitting guide-strips are formed respectively on the plane struts and on the framing. The framing carries the central portion of the upper plane and has flanges which are secured to the plane structure by bolts. A further modification is described in which the fuselage is slipped into a rectangular opening in the plane structure and secured against longitudinal movement by a forked lever adapted to engage one of the lower spars.

115,768. A. Wolff, 1472, Grove Street, San Francisco, California, U.S.A. November 3, 1917.

Propelling; Planes, Arrangement of.—A number of vanes are arranged at the rear of the propeller of an aeroplane in such a manner as to obtain a forward component from the wash of the propeller. In one form two series of vertical vanes are arranged at an inclination to the longitudinal axis of the machine and at the rear of two propellers the axes of which are at a greater inclination than the vanes. In another form the vanes are horizontally arranged behind a central propeller.

115,968. H. Phillips, Grove Cottage, West Barnham, Sussex. July 26, 1917.

Planes, Construction of.—Aerofoils for aeroplanes are constructed of thin and smooth material with the dipping front portion extended forwards with reversed curvature so that the front edge is nearly horizontal, or curved slightly upwards. Sheet aluminium alloy, sheet steel or other metal, three-ply wood, or papier mache may be used.

115,974. E. P. Wells, 94, Larkhall Rise, Clapham, London. August 1, 1917.

Roofs for Hangars, Factories, etc.—The roof covering for a hangar, factory, or other structure is laid directly on suspension members which may consist of iron bars of T or other section, or wire rope, wood, or reinforced concrete. The suspension members may be continued over supports between adjacent spans, but are preferably separately anchored, as for example, by means of a T-bar secured to a stirrup. Purlins may be clipped to the metal or wooden members and the covering, such as corrugated iron, match-boarding, etc., secured thereto. For a concrete roof, the main rods, constituting the suspension members proper, are laid in position, wire netting or mesh wire is next applied, and finally the concrete to form the supports and roof covering. Gutters are provided at the centre under a cover, which may be glazed, and there may also be added ties, ventilators, and side glazing. A floor and windows may be inserted in the frame supports.